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**Abstract:** The geologic setting of Mosul Dam is critically important for its engineering implications and its usefulness and contribution to engineering and operational decisions about the dam. The dam was constructed on alternating and highly variable units of gypsum, anhydrite, marl, and limestone, each of which is soluble in water under the environmental and hydrogeologic conditions of the dam. From a geologic standpoint, the foundation is very poor, and the site geology is the principal cause of continuing intense concern about the safety of the structure. Mineralogic variability within rock units resulted from original depositional processes that created interfaces and zones of weakness within individual beds. These natural zones of weakness now function as ingress points for seep water and allow dissolution zones to move vertically and horizontally. Dissolution is occurring at a faster rate than natural geologic processes. Sinkholes that have reached the surface recently on the east abutment indicate large-scale dissolution in the subsurface. Rock quality, grout-curtain efficiency as related to piezometer data, sinkhole development, sinkhole retreatment, dissolution rates of rock material, and water chemistry (total dissolved solids) collectively indicate that the dissolution front is moving to the east and downstream. The rate of subsurface dissolution has been increased by the presence of the reservoir. The pattern of regrouting in and between recently grouted sections of the dam shows that grouting at one location causes the flow path (seepage) of subsurface water to move to another location, but does not stop the seepage. At or above a pool depth of 318 m above sea level, the rate of subsurface dissolution increases markedly, leading to the recommendation that the pool not be raised above 318 m.

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# Preface

This report describes the geologic setting of Mosul Dam, Iraq, the analysis of which was an essential step in developing a three-dimensional (3-D) geologic conceptual model of the area of the dam. The work was accomplished by the U.S. Army Engineer Research and Development Center (ERDC), in accordance with a Memorandum of Agreement (MOA) for U.S. Army Engineer Division, Gulf Region, entitled “Project and Contracting Office (GRD/PCO) to Provide Three-Dimensional Model Development in Support of the Mosul Dam Enhanced Grouting Program. The MOA was signed on 30 May 2006 by Dr. James R. Houston, Director of ERDC, and on 28 May 2006 by COL John S. Medeiros, Sector Contracting Office, Water Lead.

This was part of a study of Mosul Dam that included development of a 3-D geologic conceptual model and numerical groundwater model; technology transfer by way of workshops in September 2006 and April 2007; and updating of a previously developed analysis of potential failure modes of the dam. The work was performed during the period June 2006 to August 2007 by a multi-disciplinary team from the Geotechnical and Structures Laboratory (GSL), Coastal and Hydraulics Laboratory (CHL), and Environmental Laboratory (EL), ERDC, Vicksburg, MS.

The primary project partners for this effort were the ERDC and GRD/PCO. The Iraq Ministry of Water Resources and the science and engineering staff of Mosul Dam also are key stakeholders who are using the products resulting from this project.

Dr. Jeffrey D. Jorgeson, CHL, was program manager for the ERDC from the beginning of the project through January 2007, after which Dr. Mark R. Jourdan, CHL, was program manager for the ERDC. Along with the program managers, contributors to the overall effort of geologic assessment included (in alphabetical order): Seth W. Broadfoot (GSL), Julie R. Kelley (GSL), Thomas E. McGill (GSL), Christian McGrath (EL), Dr. Monte Pearson (GSL contractor), Cary A. Talbot (CHL), Dr. Lillian D. Wakeley (GSL), and Dr. Robert M. Wallace (CHL). Broadfoot and Talbot built and populated the 3-D model, described in a separate report. Kelley,

Dr. Wakeley, Broadfoot, Dr. Pearson, McGrath, McGill, Dr. Jorgeson, and Talbot prepared this report.

The authors wish to thank COL Richard B. Jenkins, ERDC Commander, for his input, interest, and encouragement during the performance of this project.

Work in GSL was performed under the direct supervision of Dr. Lillian D. Wakeley, former Chief, Engineering Geology and Geophysics Branch; Pamela Kinnebrew, Chief, Survivability Engineering Branch; Dr. Robert L. Hall, Chief, Geosciences and Structures Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL. In CHL, work was performed under the supervision of Earl V. Edris, Chief, Hydrologic Systems Branch; Bruce A. Ebersole, Chief, Flood and Storm Protection Division; Dr. William D. Martin, Deputy Director; and Thomas W. Richardson, Director of CHL. In EL, work was under the direct supervision of Dr. Richard F. Lance, Chief, Environmental Processes Branch; Dr. Richard E. Price, Chief, Environmental Processes and Engineering Division; Dr. Michael F. Passmore, Deputy Director; and Dr. Beth Fleming, Director of EL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

# 1 Purpose and Scope

This report describes the process of translating historical paper information about the geology of a high-risk dam into a holistic conceptual model. A ***geologic conceptual model*** is the mental picture of what is in the subsurface or of how a surface or subsurface feature formed, based upon available information. As more data are acquired, one modifies and refines a mental picture and uses visual images such as cross sections, maps, and three-dimensional (3-D) visualization. The quality of a conceptual model depends partly on the quality and quantity of data and partly on the ability of the project team to interpret those data and present them in a way that enhances communication and understanding.

The purpose of a geologic conceptual model of Mosul Dam is to understand factors that contribute to current and future conditions at the dam, and to explain to others the causes of geologic features and geotechnical phenomena. For a geologic study associated with a large engineering project such as Mosul Dam, the geologic setting is critically important for its engineering implications and its usefulness and contribution to engineering and operational decisions about the dam.

The steps taken by the ERDC Project Delivery Team (PDT) to develop the geologic conceptual model included (1) data review and understanding of regional and local geology; (2) development of a geographic information system (GIS); (3) refining, interpolating, and interpreting the limited available data to derive a 3-D conceptual model with advanced capabilities for visualization; and (4) entering available data into appropriate software. This report gives results of the data review and describes the geologic setting of the dam as interpreted by the ERDC PDT. It describes the changes in geologic conditions that resulted from past engineering decisions and establishes the relationships between current geologic conditions and their implications for the future performance of the dam.

# 2 Background

Mosul Dam (formerly known as Saddam Dam) was constructed in the 1980s on the Tigris River near the city of Mosul, Iraq, for irrigation, flood control, water supply, and hydropower. The site was chosen for reasons other than geologic or engineering merit. From a geologic standpoint, the foundation is very poor, and the site geology is the principal cause of continuing intense concern about the safety of the structure. Specifically, the dam was constructed on alternating and highly variable units of gypsum, anhydrite, marl, and limestone, each of which is soluble in water under the environmental and hydrogeologic conditions of the dam.

Impoundment of a large freshwater reservoir in contact with these unstable geologic materials promoted continuous dissolution in the foundation and abutments, with preferential and rapid dissolution of gypsum and anhydrite layers. This condition creates a situation demanding extraordinary engineering measures to maintain the structural integrity and operating capability of the dam. The requisite engineering measures have included maintenance grouting of the structure continuously since construction. The purpose of maintenance grouting is to close water-flow pathways that open by rapid dissolution of geologic materials in the foundation and abutments. The consensus among various expert panels and engineers and scientists who have studied or worked directly on Mosul Dam is that the embankment was constructed well and is not the cause for concern. However, without continuous maintenance grouting of the foundation and abutments, the dam would fail.

The U.S. Army Engineer Division, Gulf Region (GRD), became increasingly concerned about the safety of the dam as their tenure in-country lengthened. An international panel of experts (IPE) had recommended that the structural integrity of Mosul Dam could be improved by transitioning the grouting program from 1980s practices to the best available 21st century techniques and equipment. Further, the IPE recommended that a 3-D geologic model and hydrogeologic or groundwater flow model should be developed to support the transition to enhanced grouting.

The ERDC Mosul Dam PDT was formed as an interdisciplinary working group under a Memorandum of Agreement (MOA) between ERDC and

GRD in May 2006. The principal purpose of the team was to develop a conceptual geologic model and groundwater model of Mosul Dam that would

- Be based on a thorough understanding of the regional, local, and site-specific geologic conditions, including geologic processes and structures and geochemistry
- Provide a 3-D visualization tool to enable geologists and engineers on the Mosul Dam staff to make best use of previously unusable or minimally usable data
- Establish the basis for data files with positional accuracy for future dam operations and maintenance
- Provide to the Mosul Dam staff a geologic tool that can be used into the future to evaluate the performance of ongoing and future grouting and monitoring programs
- Improve understanding of the foundation and reservoir geology, geochemistry, and hydrogeology
- Improve understanding of the effects of grouting on the foundation's ability to withstand further dissolution
- Improve understanding of how and why sinkholes and other dissolution features are forming
- Provide the geologic data for the software that will support and operate the Enhanced Grouting Program.

To accomplish these purposes, the ERDC PDT for geologic assessment included expertise in geology, geochemistry, geological engineering, geographic information systems, hydraulic engineering and hydrology, and 3-D modeling, with team members from ERDC Coastal and Hydraulics, Geotechnical and Structures, and Environmental Laboratories, as well as outside consultants. This report describes the geologic setting of the dam, geochemical processes of rock dissolution, changes in rock properties with time, and the engineering implications of properties and processes. This holistic geologic and engineering understanding was the basis for developing the 3-D conceptual geologic model (described in "Geologic Conceptual Model of Mosul Dam," Wakeley et al. 2007). It also was supporting technical information for an update of potential failure-mode analysis described in a separate document.

# 3 Review of Geologic Data

The primary source of information for the ERDC project was a 13-volume compilation of data and information on Mosul Dam spanning its construction and 20 years of operation, known as the Mosul Dam Library of Documents (LOD) (Washington International/Black and Veatch 2004; augmented in 2005). Based on information provided by GRD in the MOA, the ERDC team expected the LOD to include most of the geologic data necessary to form the basis of the conceptual model. The ERDC scope of work had been written with the understanding that the model would be based on pre-existing LOD information, without benefit of new field studies.

While the LOD contained enough geologic information to define a conceptual picture of the regional geology, most of the data predated widespread use of GIS technology. The LOD included no exportable data files (such as Excel or other spreadsheets). None of the information such as descriptive logs from geological borings was accompanied by numerical location information. This lack of exportable or positional data greatly complicated the process of generating a GIS and a 3-D conceptual model, both of which are essential to site-specific interpretation and communication of engineering significance.

The ERDC PDT received some recent (2005 and 2006) spreadsheets and data in other formats directly from Mosul Dam staff during a workshop in Vicksburg, MS, USA, in September 2006. The files included the “official” geologic cross section of the dam and some plots and text data describing sections of the dam that have been grouted recently (since 2002, although these data did not include information about depth or geologic unit grouted, or amounts of grout per unit time in any digitally located positions). Also provided in September 2006 were data from monitoring water chemistry and piezometer readings in 2005 and part of 2006. These data included total dissolved solids of seep water reported with time, and were valuable in understanding current conditions at the dam. The ERDC team presented figures and interpretations derived from these data sets at the Technology Transfer Workshop in April 2007. Also, a team from GRD and other U.S. Federal agencies visited the dam site in December 2006, and provided new digital photos, descriptions of current visible conditions, and

rock samples from recent cores drilled in the east (left) abutment. The ERDC team used the photos and rock samples to crosscheck interpretations of older data.

An additional component of the data review was locating and analyzing the usefulness of data from other sources, including open literature. Professional publications on such topics as sinkholes in evaporite rocks, gypsum karstification in the Mosul area, and the influence of Mosul Dam on sediment transport and geomorphic processes in the Euphrates-Tigris Basin all contributed to the conceptual geologic model of the region. A partial list of publications used for background information appears at the end of this report (References and Additional Data Sources). Publications by Jassim et al. (1997, 1999) and Guzina et al. (1991) were especially informative.

# 4 Geographic Information System

A geographic information system is essential for managing the quantity of geographic, geologic, and geotechnical data involved in developing 3-D conceptual and numerical models. Initial digital data sets for the Mosul Dam GIS came from military sources, other federal agencies such as the U.S. Geological Survey, and commercial sources.

The ERDC constructed a GIS of Mosul Dam to provide a tool to manipulate and manage data sets and to define the geospatial components of the data. Data identified as essential to this effort included project drawings, geologic cross sections, Lugeon-value plots, and logs from geotechnical borings. Prior to the ERDC effort, no data for the dam were in spatially referenced digital files. The ERDC team scanned and georectified all images within the geographic boundaries of dam documentation.

Using commercially available software from Environmental Systems Research Institute (ESRI), the ERDC team constructed layers from digital aerial photographs and other imagery, providing fixed points to which other data sets could be matched or rectified. Surface topography, drainage patterns, and other features were available digitally. The team added layers for rock and soil types, geologic structural features, locations of piezometers, locations of sink holes, and other critical information. Developing the GIS was accomplished by a combination of interpretation of imagery and creation of new files by digitizing and rectifying paper printouts from the LOD and from dam staff.

In addition to the data sets listed above, data layered into the GIS include cross sections pre- and post-dam construction, Lugeon values, geologic borings, as-built main scheme drawings, and other drawings not available in the LOD. Tabular data sets with associated coordinates also were incorporated into the GIS. Instrumentation drawings, such as piezometer location maps, were scanned, digitized, rectified, and imported to the GIS. Digital files and large-format plots from many of the documents scanned by the ERDC were provided to dam staff during the workshops in September 2006 and April 2007. The ERDC also provided digital files of geologic data to Gannett Fleming, Inc., for use in the IntelliGrout®

software, which is the platform for the Enhanced Grouting Program selected for the dam.

Digital products derived from the GIS were exported to the software system that will be used for the hydrogeologic model. The model will be developed using the U.S. Department of Defense Groundwater Modeling System (GMS). Panel diagrams and 3-D visualization products in this report were generated from the ERDC GIS using GMS.

The digital 3-D representation of the conceptual geologic model consolidates data that previously could be viewed only as individual pieces of paper or as portable document format files. With the 3-D model, each piece of the total geologic puzzle can be displayed and visualized in relation to any or all of the other pieces. It incorporates site-specific interpretation and interpolation provided through the analytical efforts of the ERDC team. The 3-D tool provides a holistic picture of conditions under the dam relative to rock type, unit thickness and distribution, and geologic structures. It reveals critical features such as southeast-dipping geologic units that can focus the directional movement of dissolution. The georeferenced geologic information and visualization options of the 3-D model will facilitate future maintenance grouting and operation of the dam.

# 5 Geologic Setting of Mosul Dam

A geologic conceptual model is developed to establish a scientific context for the geologic features at the surface and in the subsurface, and to understand how a feature formed, based on understanding what is geologically possible at a given location. Through interpretation of all available data, the conceptual model defines the most likely sequence of processes and events that explain observed geologic evidence and features (Dunbar et al. 2001). These geologic features have engineering implications to the operation, grouting, and long-term stability of the dam.

The ERDC Mosul Dam support team developed a geologic conceptual model of the immediate area around Mosul Dam, the region of northern Iraq surrounding the dam, and the general geologic structure of the Arabian tectonic plate.

In this case, the model confirms that the sedimentary rock units in the area formed by processes of evaporation, precipitation, and alteration. After deposition, the rock units were subjected to regional tectonic movement that folded once-horizontal layers into anticlines and exposed steeply dipping, weathered beds as seen in recent photographs taken at the dam site. The GIS and geologic conceptual model were used to build the concepts and holistic interpretations of data into both visual products and predictive tools. Using GIS and GMS, the ERDC team translated this conceptual model into tools that can be used to visualize the surface and subsurface features of Mosul Dam. These tools also were provided to Gannett Fleming, Inc., for use in the IntelliGrout® system.

## Geologic conceptualization

The ERDC team developed a geologic conceptual model at three levels of detail: regional, local, and site geology. Figure 1 illustrates the three levels of geologic detail. The regional geologic setting, or the Big Picture, describes processes of deposition and plate tectonics that caused the large-scale structural features of the Arabian Plate. Regional geology and geologic processes are described and interpreted for northern Iraq. Site-specific geology includes detailed stratigraphy and geologic features in the foundation and abutments of the dam itself. Although our conceptualization covers all three levels, the 3-D visualization and modeling tools

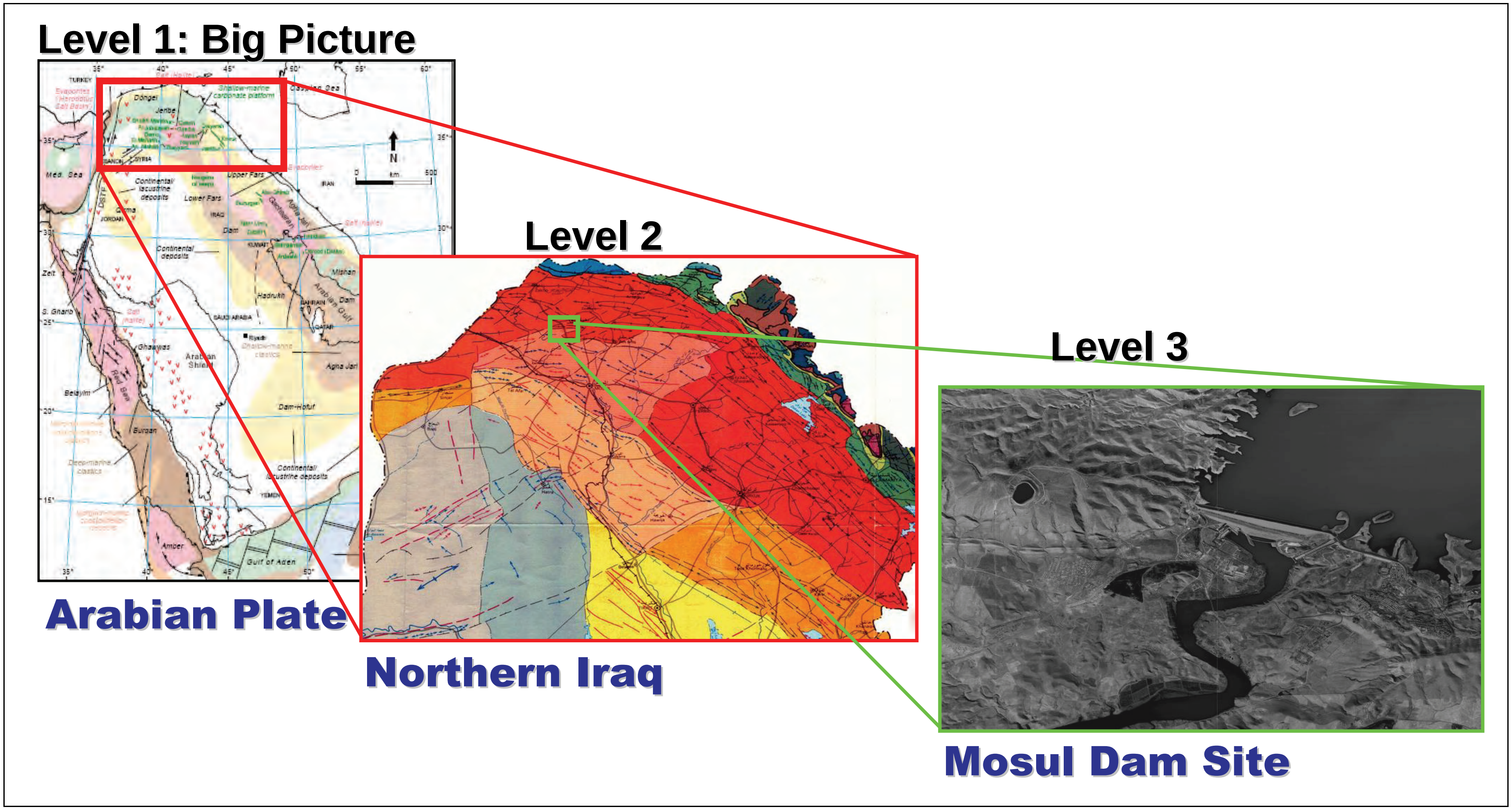


Figure 1. Three levels of detail in ERDC Conceptual Model of Mosul Dam. Level 1 is geologic history and large-scale processes of the Arabian Plate; Level 2 is specific environments of deposition and erosion in northern Iraq; Level 3 is site-specific detail about the geo-environment of Mosul Dam, especially its foundation and abutments. Approximate axis of eastward-plunging Butmah Anticline indicated by green arrow at Level 3.

developed by the ERDC apply only to the geology at the dam site. The following sections describe the principal geologic features of the three levels of the geologic conceptual model.

## Level 1: The Big Picture

### Description

The Arabian Plate is a stable portion of the earth's crust surrounded by tectonically active margins (Fox and Ahlbrandt 2002). The plate was part of the supercontinent of Gondwana throughout much of geologic time. Two episodes of rifting, from the Permian Period (286 to 245 million years ago (Ma)) to the Jurassic Period (206 to 144 Ma), formed the Neo-Tethys Ocean (Sadooni and Alsharhan 2004) and were followed by periods of subsidence and sediment accumulation (Kazmin 2002, Sharland et al. 2001). Final closure of the Neo-Tethys Ocean happened in Middle Miocene (15 Ma) when the Arabian Plate, drifting northward, collided with Eurasia.

Tectonic activity of the Neo-Tethys Ocean area along with fluctuations in sea level influenced the type and amount of sedimentation on the Arabian Plate. At times, the plate was inundated with ocean water, resulting in the deposition of limestone. Similarly, in the plate area that is now Iraq, shallow marine shelf and near-shore zones accumulated carbonate and evaporite sediments. The compressional forces associated with the collision of the northern margin of the African-Arabian Plate with Eurasia (Miocene Period) formed the Taurus Mountains to the north and the Zagros Mountains to the east (Fox and Ahlbrandt 2002).

Northern Iraq lies within the Unstable Shelf (Buday 1980) of the Arabian Plate and is divided into three tectonic zones. The High Folded Zone on the eastern border of Iraq includes the Zagros Range (4300-m elevation). To the west and parallel to that zone is the Foothill Zone, a 200-km-wide northwest-to-southeast-trending belt consisting of low anticlinal ridges. These foothills are separated by broad, shallow synclines filled with recent (Quaternary Period) clastic sediments. The Mesopotamian Basin Zone lies to the south and west and contains the alluvial deposits of the Tigris River and the Euphrates River floodplains. Compressional forces during the Pliocene Epoch (5.3 to 1.8 Ma) created these tectonic zones.

With the closing of the Neo-Tethys Ocean, sedimentation changed from marine to marginal-marine and, finally, to clastic during the Miocene Epoch (23.8 to 5.3 Ma). As a result, many of the exposures in the Foothill Zone are of Late Miocene age (11.2 to 5.3 Ma) or younger and are represented by the Jeribe Limestone Formation (locally referred to as Euphrates-Jeribe Limestone Formation; Late Miocene) and the Upper and Lower Fars Formations (Middle Miocene).

### How the Big Picture affected the dam site

The active-fault-bounded Mosul Block has influenced sedimentation in the area near Mosul Dam since the Early Cretaceous Period (144 to 97.5 Ma) (Jassim et al. 1997). The Mosul Block (also referred to as the Mosul Uplift) created a ridge and divided the sedimentary basin during the Miocene into two parts—the western Sinjar Basin, extending into Syria, and the eastern basin, extending to the southeast toward Iran (Jassim et al. 1997).

The Lower Fars Formation is the predominant sedimentary unit in the Mosul Dam area. A lagoon-and-sabkha environment existed in the Miocene (23.8 to 5.3 Ma) where evaporites, marls, carbonates, and claystones of the Lower Fars Formation were deposited. The Lower Fars Formation is nearly 250 m thick near Mosul (directly over the Mosul Uplift area) and is 600 m thick in Sinjar (in the basin), to the west (Jassim et al. 1999). The name Fatha Formation was introduced by Jassim et al. (1984, 1986) to replace the designation Lower Fars Formation.

## Level 2: Regional geology and processes

The topography and subsurface geology in the area of Mosul Dam are the result of complex depositional processes and subsequent tectonic activity and erosion, all of which exerted control over the modern geologic setting of the dam. This section describes the processes of deposition and erosion in the geologic history of Northern Iraq that are the scientific basis for the engineering challenges of Mosul Dam.

### Sabkha depositional environment

The foundation rocks beneath Mosul Dam are predominantly of the Late Miocene-age Fatha Formation and were deposited in lagoonal and sabkha environment. A sabkha, an Arabic word translated to "salt flat," is a supratidal (supralittoral) environment of sedimentation formed under arid to

semiarid environments on coastal plains where infiltration of fresh water is restricted and just above the normal high-tide level (Patterson and Kinsman 1981). An active sabkha has low relief—generally less than 50 cm—and the resulting sediments are geologically complex. Eolian deposits, tidal-flood deposits, carbonates, and evaporite minerals all characterize a sabkha setting, and they change and interfinger both horizontally and vertically within a single geologic layer.

Understanding a modern sabkha environment provides a geologic key to understanding the depositional environments of the Late Miocene (11.2 to 5.3 Ma) in the area. The subsurface rock formations in the Mosul Dam area are repeated sequences of marl, gypsum, and carbonates, which are the same sequences that result from depositional processes observed in modern sabkha settings.

In an active sabkha, the amounts and distribution of calcite, gypsum, and anhydrite change through time depending on the movement and chemical composition of groundwater in pores in the sediment. Once the sediments are in place and have been buried by subsequent deposition, chemical and physical changes continue in response to changes in chemical composition and in amount and movement of groundwater.

Modern examples are present along the Persian Gulf shoreline. Persian Gulf sabkhas have been studied extensively and were first described by Curtis et al. (1963), Kinsman (1964, 1969), Evans et al. (1969), and Butler (1969). In a coastal sabkha, the water table is near the surface (usually less than 2 m depth) and the hydrology of the setting controls rate of deposition and type (chemical composition) and amount of evaporite minerals.

Warren and Kendall (1985) described the setting of a modern sabkha in Abu Dhabi, Persian Gulf. A transect landward across the surface might be as much as 16 km wide and passes from offshore marine sediments, through oolitic grainstones, lagoonal sands and muds, intertidal algal mats and, finally, through a mid-sabkha sequence. The mid-sabkha sequence is supratidal and is characterized by anhydrite overlying gypsum often with a halite crust.

Most of the initial evaporite deposition actually occurs in a 1-m-thick zone immediately above the water table (Warren and Kendall 1985). Gypsum is

abundant, sometimes as belts within the sabkha or in thick layers of crystal "mushes," from precipitation in the vadose and capillary groundwater zones. Gypsum also can form in the upper phreatic zone (Schreiber and El Tabakh 2000). Anhydrite replaces the gypsum above the water table and also can rehydrate during rainy periods and transform again to gypsum. The amounts and distribution of these minerals is changing continuously, depending on the movement of interstitial brine. Diagenesis (chemical and physical alteration) continues to change the mineralogy after the sediments are buried by subsequent deposition.

The Fatha Formation is up to 352 m thick at the dam and has an upper and lower member. The lower member is dominated by carbonate in its lower part (locally called "chalky series") and gypsum in its upper part, and is capped by a limestone marker bed. The upper member, a green and red claystone with gypsum, is present in thin outcrop belts around the Butmah Anticline.

The Fatha Formation is up to 350 m thick at the dam and is described in the area by Jassim et al. (1997). Original deposition of the Fatha Formation followed the usual cyclic pattern of sabkhas and resulted in alternating layers of marl, gypsum, and carbonate. The formation has an upper and lower member. The lower member is dominated by carbonate in its lower part (locally called "chalky series") and gypsum in its upper part, and is capped by a limestone marker bed. It has a thickness of 352 m near Mosul Dam (LOD, Vol 5). The upper member, a green and red claystone with gypsum, is found in the synclines of the Foothill Zone and in thin outcrop belts around the Butmah (locally called Dar Maleh) anticline that comprises the west (right) abutment of the dam and adjacent parts of the reservoir floor.

### Development of karst and breccia

Rock layers near and under Mosul Dam are subject to dissolution and the development of karst features. Karst topography is characterized by landforms that result from subsurface dissolution of water-soluble geologic materials and is often surficially manifested as dolines (sinkholes). Dolines are "closed circular to elliptical hollows or depressions, often funnel shaped, with diameters ranging from a few meters to a few kilometers and depths ranging from a meter to hundreds of meters" (Warren 2006). Dolines form after rock dissolution creates subsurface cavities that cause the loss of support of the overlying material and result in a collapse feature

recognizable at the surface. Worldwide, karst features are more commonly associated with limestone. Evaporite minerals such as anhydrite and gypsum also are water soluble and are known to develop karst. Gypsum dissolves 10 to 30 times faster than limestone (Warren 2006) and is present throughout the rock in the foundation and abutments of Mosul Dam.

Dolines and dissolution features were present in the Mosul Dam area before the construction of the dam. A cave was found upstream of the dam on the east side of the reservoir, and several sinkholes have been noted 8 km north of the dam site (LOD, Vol 5). Jassim et al. (1997) studied the development of karst features around the city of Mosul and concluded that 99% of karst in the area forms in gypsum layers of the Fatha Formation.

Gypsum breccia layers exist within the Fatha Formation and have proven to be the most problematic rocks in the foundation. Breccia is evidence of a subsurface dissolution zone within a layer of gypsum. Pieces of partially dissolved rock may collect on the floor of a void space as a layer of rubble within. The main breccia body contains fragments or clasts of limestone, dolomite, or larger pieces of insoluble rocks of collapsed material. The upper portion of the accumulation grades upward from rubble to crackle mosaic breccia and then a virtually unaffected competent overburden (Figure 2). Breccia also may form without the intermediate step of an open cavity, by partial dissolution and direct formation of rubble.

As groundwater moves through the rubble, soluble minerals are carried away, leaving insoluble residues of chert fragments, quartz grains, silt, and clay in a mineral matrix. As bedded solution-collapse breccias evolve and the most soluble components are removed, permeability eventually may be reduced by the accumulation and consolidation of the insoluble matrix material (Warren 2006) that may be cemented with less-soluble minerals. These processes result in geologic layers with lateral and vertical variability on scales of micro-meters to meters.

Anhydrite is also present within the foundation rocks at Mosul Dam. Unfractured anhydrite is denser, harder, and less permeable than gypsum. Gypsum is formed by the hydration of anhydrite, and the hydration causes an increase in volume of approximately 30 to 50% (Jennings 1985). The resulting volume increase can cause further micro-fracturing in the rock and promote dissolution by providing pathways for free movement of water.

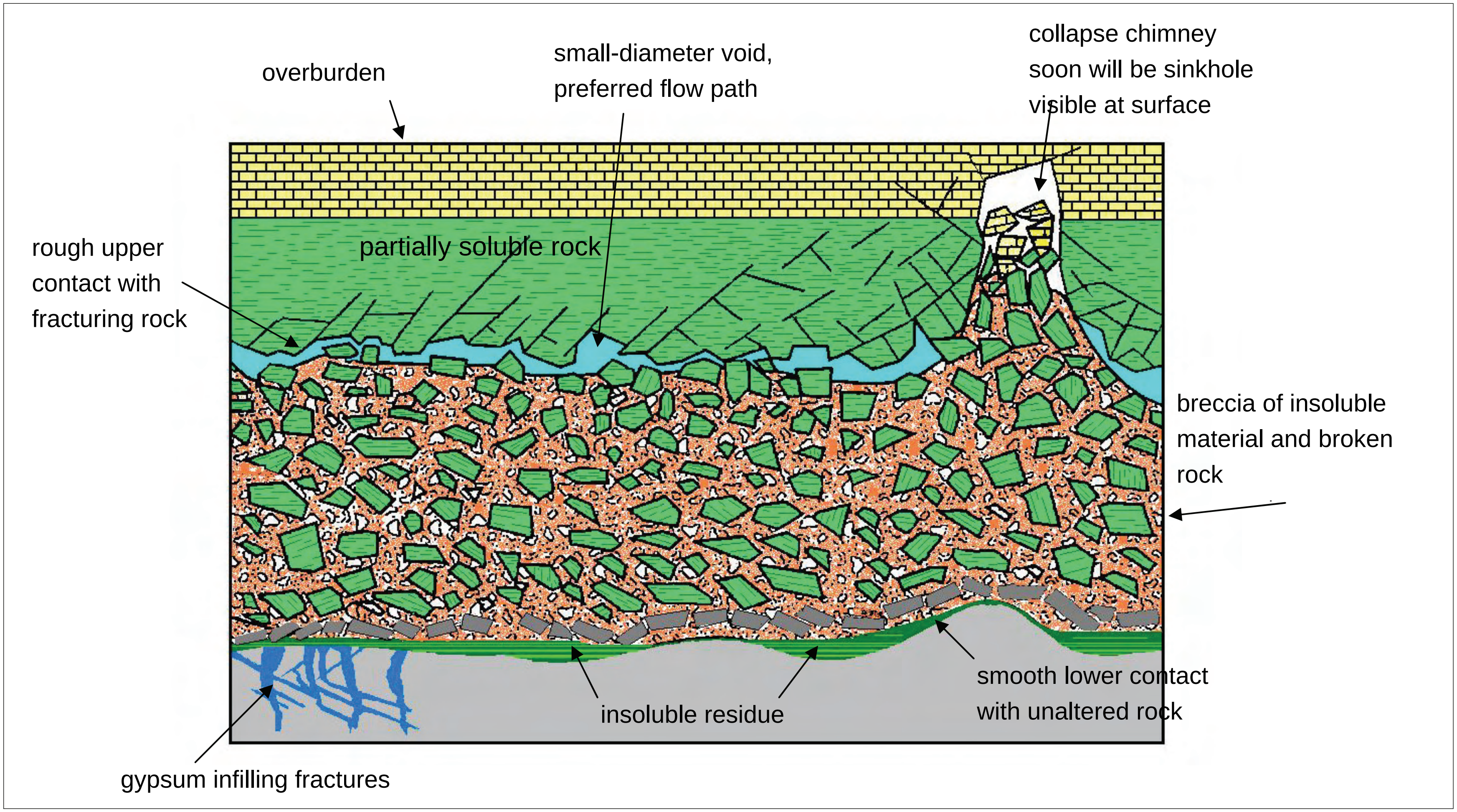


Figure 2. Development of breccia within a layer of gypsum (Warren 2006).

### Historic river channel

The Tigris River floodplain (Figure 3) in the dam area has been in much the same location since the Pleistocene (1.6 Ma to 10,000 years ago) (Jassim et al. 1999). Over time, the river channel has migrated from east to west as evidenced by the location of old abandoned river terrace deposits primarily on the east side of the river (Jassim et al. 1997). Deposits within the active river channel consist of loosely cemented conglomerates, sands, and marls. Because of their high permeability, these materials would likely be a natural conduit for groundwater. However, large volumes of the terrace gravels were removed during construction. Remaining terrace deposits are not continuous across the dam site and are not in configurations to provide subsurface flow pathways for water from the reservoir.

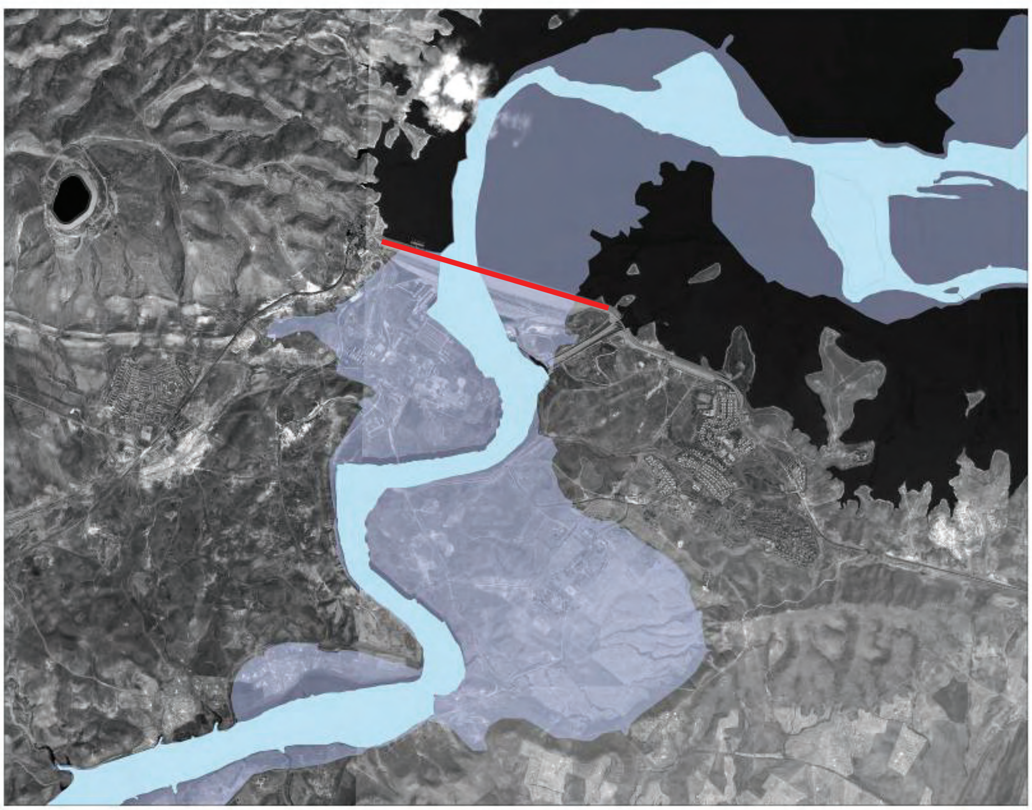

Figure 3. Pre-dam Tigris River channel (light blue) and floodplain (gray) are shown shown above Mosul Dam (red line) superimposed on the reservoir (shown in black). The recent Tigris River channel (light blue) and floodplain (gray) continue below Mosul Dam (M. L. Pearson, S. W. Broadfoot, and J. R. Kelley).

## Level 3: Geology of the foundation of Mosul Dam

A hyperspectral image of the dam and its immediate vicinity shows a number of sinkholes that are visible downstream of the dam and on the east abutment (Figure 4). Sinkholes, caves, and cracks appeared in and around the dam foundation during construction and reservoir impoundment (in 1984). Several horizons of foundation materials are micro-fractured and highly permeable, and are undergoing dissolution. These conditions require the current and continuous grouting program that was initiated during construction in an effort to minimize further dissolution and karst development. Major functional integrity issues and concerns with the dam have always been associated with the nature of the foundation materials and with manifestations of continued dissolution such as sinkholes, seepage, and cracks in the embankment.

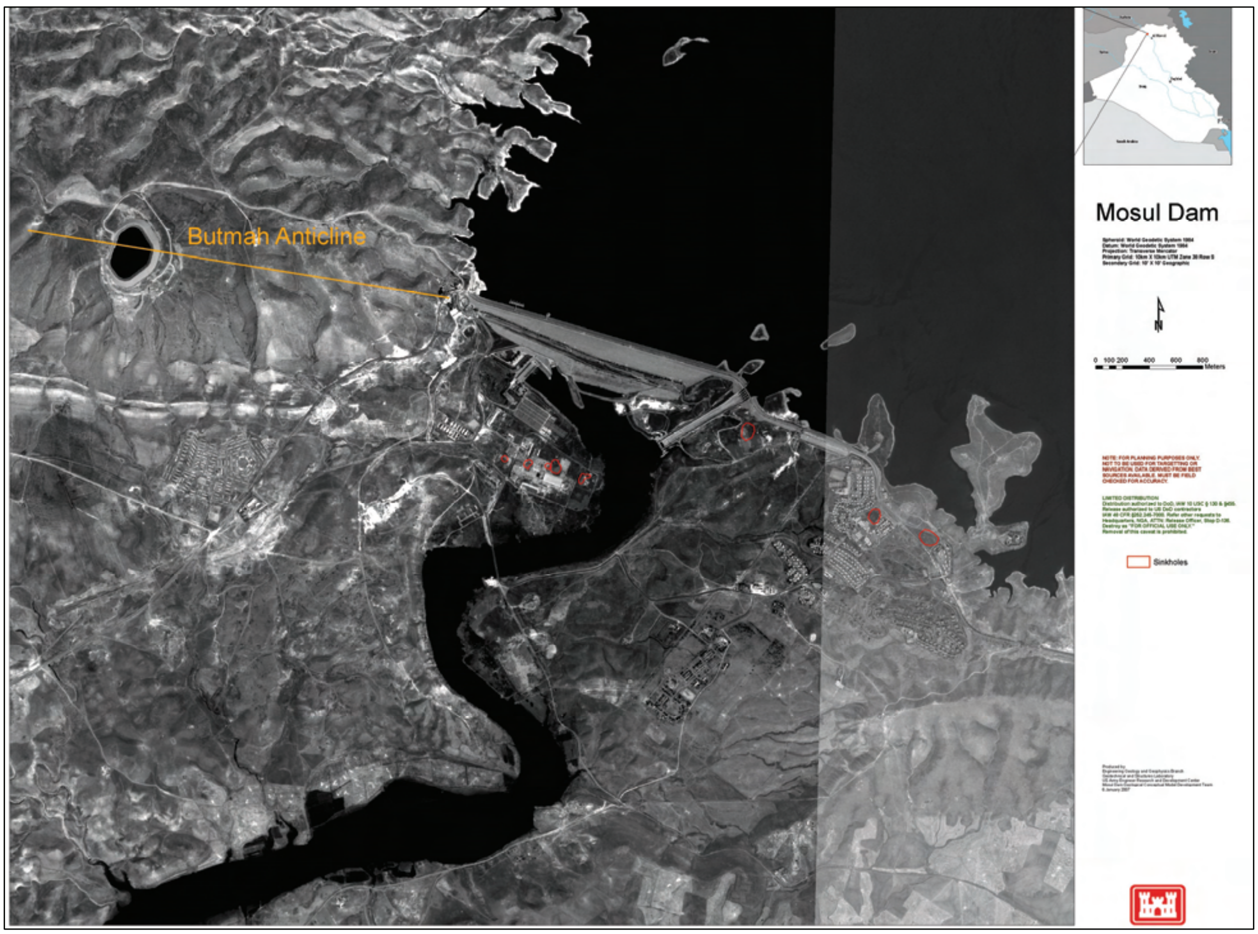


Figure 4. Hyperspectral image of the vicinity of Mosul Dam showing locations of sinkholes (red dots; compiled by S. Broadfoot using GIS).

A geologic investigation was conducted prior to dam construction and is documented in the Mosul Dam LOD. A lithostratigraphic table (Figure 5) of the foundation geology of Mosul Dam was included in the LOD, with numerous reports and hand-drawn geologic cross sections. Characteristics are listed for both unaltered rocks in the foundation and for those that have undergone alteration and dissolution. Stratigraphy of the rock layers in the dam foundation and immediate area near the site was characterized and defined as summarized below.

### Stratigraphy—Euphrates-Jeribe Limestone

The oldest rocks exposed in the area are from the Euphrates-Jeribe Limestone Formation of Late Miocene age (11.2 to 5.3 Ma). Jassim et al. (1997) described the unit as being composed of "bioclastic recrystallized, dolomitized limestone, clayey dolostone and sporadic thin gypsum," with a total thickness of 50 to 60 m. Surface exposures of Euphrates-Jeribe Limestone occur in some deep gullies and in subsurface samples retrieved in cores from the anticline structures in the area around Mosul.

At Mosul Dam, the limestone is found in the west bank only. The formation dips approximately 12 deg to the east within the lower part of the Butmah plunging anticline structure (Jassim et al. 1997). The Euphrates-Jeribe Limestone Formation overlies a weathered unit of marly dolomitic breccia that is locally referred to as the "bauxite" layer. The bauxite layer lies unconformably over the older Jaddala-Sinjar Limestone Formation of the Oligocene Epoch (33.7 to 23.8 Ma) that does not crop out in the area. (Note: This layer of dissolution breccia was erroneously named bauxite during geologic studies of the 1980s. We use the term "bauxite" only to connect our work to documentation in the LOD of the initial site characterization.)

### Stratigraphy—Fatha (Lower Fars) Formation

The Fatha Formation is divided locally into two units referred to as the Upper Fars and Lower Fars "Groups." The Lower Fars Group of the Fatha Formation forms the predominant group of rocks in the foundation. The unit contains gypsum and anhydrite layers interbedded with marls, limestones, and claystones (Jassim et al. 1999) and can be further divided into the Upper and Lower Marl Series and the F-bed Limestone.

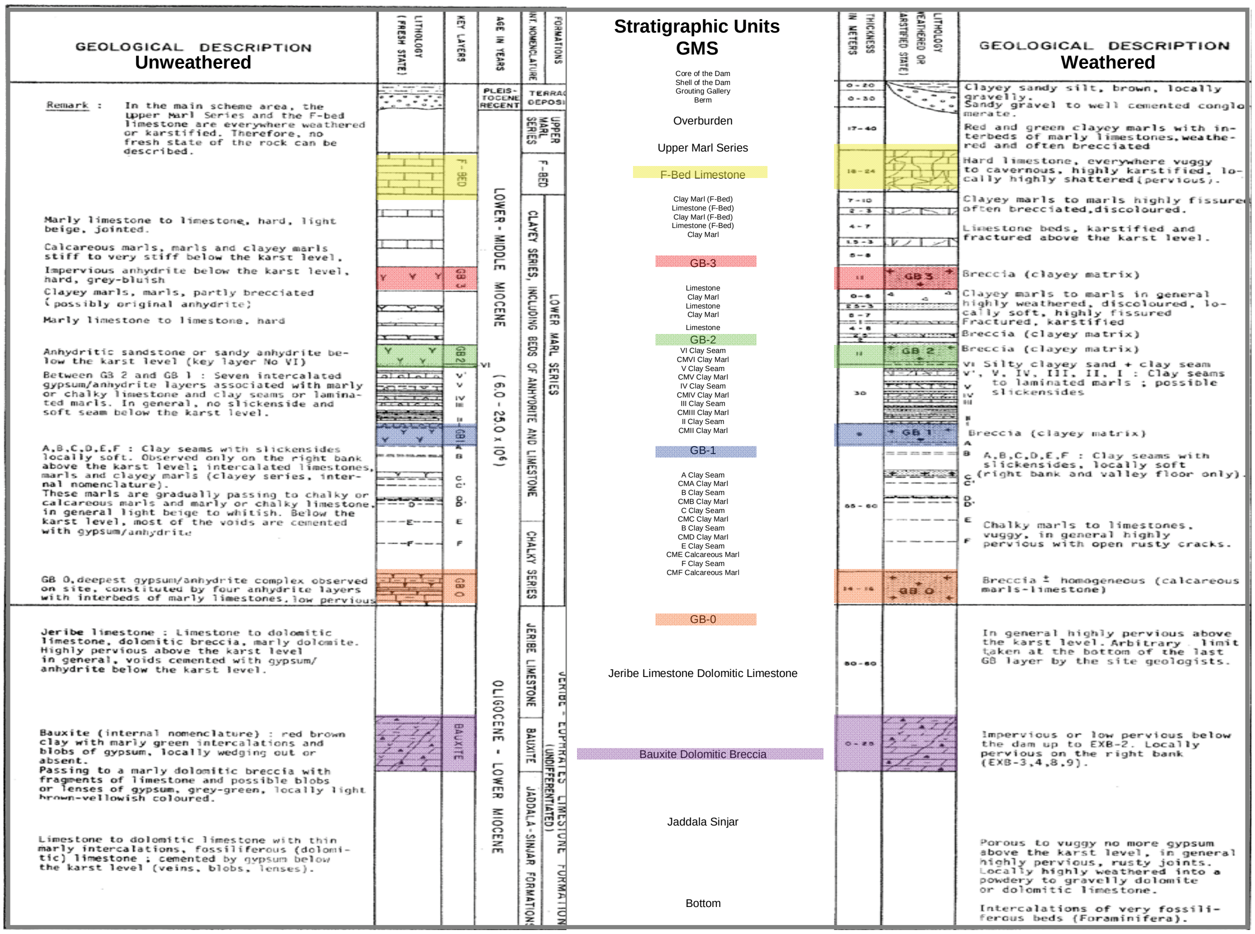


Figure 5. Lithostratigraphic table of foundation materials at Mosul Dam (LOD, Vol 5; modified by J. R. Kelley and M. L. Pearson).

The Upper Marl Series is found only on the east bank of the dam site and consists of interbedded, marly limestone and calcareous marls that are usually highly fractured.

The F-bed Limestone is 20 to 24 m thick and forms distinctive outcrops on both sides of the valley (LOD, Vol 5). The upper half of the unit consists of highly fractured, brecciated limestone beds, and the lower half is interbedded marls and limestones. It is thought that an increase in volume, produced during alteration of interbedded anhydrite to gypsum, generated sufficient pressure to fracture the formation. The main part of the spillway was constructed on the F-bed Limestone. Initially, the F-bed Limestone was one of the problem areas taking large quantities of grout.

The Lower Marl Series is approximately 180 m thick in the area and consists of interbedded layers of anhydrite/gypsum, marls, and limestones with thin clay seams. The Lower Marl Series is locally subdivided into the

Clayey Series (150 m thick) and the Chalky Series (20 to 30 m thick; LOD, Vol 5). Four dominant anhydrite/gypsum breccia layers have been identified as marker beds and are designated (from upper to lower) GB3, GB2, GB1, and GB0. The lowest boundary of the Lower Fatha Formation is the base of the GB0 bed.

### Stratigraphy—overburden

Recent alluvium of the Tigris River, composed of poorly consolidated sand and gravel, is exposed downstream in the valley as well as in terraces at elevations 80 m above the valley floor upstream on the east abutment. The lower terraces were used as borrow areas for materials for the core of the dam and they consist of sandy clayey silt in layers up to 20 m thick (LOD, Vol 5). Some of the terrace deposits are partially cemented, forming a conglomerate with a calcareous matrix. Jassim et al. (1997) noted that terrace deposits have been readily differentiated and mapped only on the east bank, because much of the terrace material upstream and to the west of the dam was eroded away as the river migrated from east to west. Lower terrace deposits are visible downstream on both sides of the channel.

According to information in the LOD, the original plan for the dam was to construct part of the dam core on river terraces that were thought to be structurally competent conglomerate deposits. During construction, some of the gravel was removed and was determined to be inadequate as foundation material. The foundations of the fuse plug spillway, the main spillway, and the powerhouse were partly excavated through the terrace deposits and founded on Upper Marl Series material.

# 6 Geologic Challenges to Dam Integrity

## Geology of the abutments and foundation of Mosul Dam

### Geologic structures on the right (west) abutment:

The Butmah Anticline comprises geologic units dipping north and south and plunging toward the dam from the west (right abutment) (anticline indicated in Figures 1 and 4). These steeply dipping geologic units dip toward the reservoir on the north flank and away from the dam on the south flank, and extend under the reservoir floor from the west. Figure 6 is taken from the ERDC 3-D geologic conceptual model, showing the contrast in dip on the west and east abutments of the dam. As are all the gypsum beds in the area of Mosul Dam, gypsum units in the anticline are undergoing dissolution. However, because of the contrast in dip direction on the two flanks of the anticline, and because the upper geologic units in the anticline have been truncated by erosion and therefore are not connected from upstream to downstream, the anticline is not a path of preferred hydraulic conductivity from the reservoir through the abutment.

### Geologic structure of the left (east) abutment

In contrast to the steeply dipping beds in the right abutment, geologic units in the east (left) abutment dip at a shallow angle (9 to 12 deg) to the south and east. Because of the direction of flow of the river and the regional dip to the southeast away from the northern mountains, southeast is the preferred direction of groundwater flow on the east (left) abutment. Thus, the geologic structure of the left abutment promotes flow of water from the reservoir into the subsurface geologic units. Stated another way, the geology of the east (left) abutment promotes continuous hydraulic connectivity between the reservoir water and downstream rocks in the subsurface. The reservoir thus provides an ample supply of water for subsurface dissolution of east-abutment rocks.

### Foundation materials

All of the geologic materials in the foundation and abutments are microfractured, highly permeable, and are readily undergoing dissolution. Because of the long residence time of the river in a constricted part of the valley, dissolution was occurring in the rocks beneath the river for

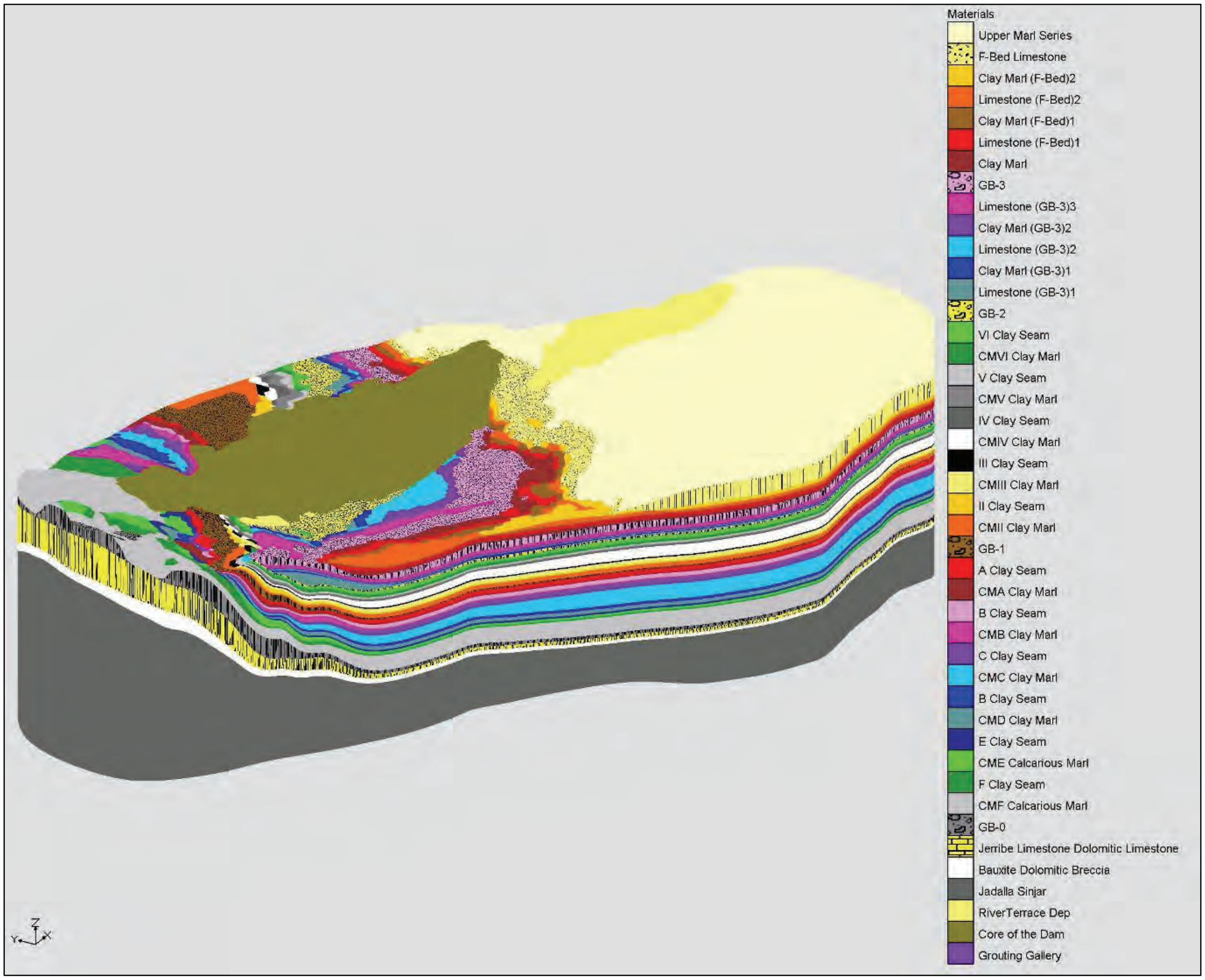


Figure 6. Two-dimensional projection of an oblique view of the 3-D conceptual model, looking upstream from the southwest toward the downstream face of the dam. Broad yellow area is surface expression of southeast-dipping geologic units on the east abutment; contrasting to complex exposed geology of steeply dipping units under the dam and reservoir and on the west abutment, where the Butmah Anticline is the dominant geologic structure. (Figure from ERDC 3-D geologic model in GMS.)

centuries to millennia before construction of the dam. This long-term dissolution is evidenced by the dissolution features visible in photos taken during construction (Ayoub 2006, photographs shown at the Sep 2006 workshop in Vicksburg, MS) (see Figure 7).

Sinkholes, caves, and cracks appeared in and around the foundation of Mosul Dam during construction and reservoir impoundment. These conditions require the current and continuous grouting program that was initiated during construction in an effort to minimize further dissolution and karst development. Major functional integrity issues and concerns with the dam have always been associated with the nature of the


Figure 7. Photo taken during construction of Mosul Dam (1982-1983) showing caves, breccia, and collapsed bedding exposed during excavation, attributed to prehistoric and historic dissolution of gypsum prior to dam construction. (Photo provided by A. T. Ayoub.)

foundation materials and with manifestations of continued dissolution such as sinkholes, seepage, settlement, and formation of cracks visible at the surface.

A geologic investigation was conducted prior to dam construction and is well documented in the Mosul Dam LOD. Figure 5 summarizes the stratigraphy in the foundation geology of Mosul Dam. Characteristics are listed for both unaltered rocks in the foundation and for those that have undergone alteration and dissolution. Stratigraphy of the rock layers in the dam foundation and immediate area near the site was extensively crosschecked and built into a geologic conceptual model by the ERDC, and translated into a digital conceptual and hydrogeologic model. Descriptions

of stratigraphic units, given in Chapter 5 of this report, were included in the notebooks and CD from the workshop "Three-Dimensional Model Development in Support of the Mosul Dam Enhanced Grouting Program," April 15 through 26, 2007, Ankara, Turkey.

The main part of the spillway was constructed on a geologic unit called the F-bed Limestone. The F-bed is not pure limestone, but includes discontinuous zones of gypsum and other minerals. At the time of construction, the F-bed Limestone was one of the problem units that required large quantities of grout. It did not have engineering properties expected for a limestone, and was a less-than-ideal foundation for construction of a very large concrete structure such as the spillway.

The overburden is recent sediment deposited by the Tigris River, and is composed of poorly consolidated sand and gravel. It is exposed downstream in the valley as well as in terraces that are remnants of prehistoric stream elevation at elevations up to 80 m above the valley floor upstream on the east abutment. The lower terraces were used as borrow areas for materials for the core of the dam. Some of the terrace deposits are partially lithified (particles held in natural mineral cement) forming a conglomerate with a calcareous matrix. Lower river terrace deposits are visible downstream on both sides of the channel.

## Geologic processes that impact operation of the dam

### Dissolution and the dissolution front

Within the foundation rocks at Mosul Dam, unweathered anhydrite and gypsum are known from drilling and water testing to be solid and of low permeability in places. However, sinkholes, voids, and cracks were observed during construction and were recognized as indicators that dissolution processes were active in the area. During excavation and construction, consulting engineers knew from lithologic compositions, formation alterations (to breccia or fine-grained material), regional dip of beds, and water pressure testing that dissolution features existed within a zone adjacent to fairly intact rocks. This zone or dissolution front was located under the existing riverbed and extended to a depth of 100 m below the projected base of the dam (Guzina et al. 1991). The front appeared to have moved downdip and in a southeasterly direction and is the result of eons of precipitation and fluvial events within the old river channel.

The ERDC analysis indicates that the natural process of dissolution was enhanced and accelerated by impoundment of the reservoir. Reservoir water is undersaturated with respect to calcium sulfate (gypsum or anhydrite; see Chapter 7 of this report). It provides an unlimited supply of dissolving fluid, driven by the greatly increased hydraulic head of a deep reservoir, to dissolve and alter the rock material.

As dissolution progresses from the movement of groundwater through the geologic units, the rock is altered to brecciated material of parent rock and clay. The dissolution front or transition zone is problematic because, as material weathers, soluble minerals and fine-grained particles wash out leaving fissures or voids that increase permeability. As greater amounts of water pass through the fissures, the dissolution rate increases. Dissolution causes loss in volume and thus triggers more dissolution by causing additional fracturing and settling.

A modeling effort was completed by the ERDC team to define areas of greatest dissolution at the time of construction. Values for grout take were recorded on a cross section at the dam crest in 1984 (LOD, Vol 10). These values were plotted using Geostatistical Analyst software (ESRI) to determine a spatial correlation. A kriging procedure was used to predict unknown values from data observed at known locations with a variogram. Using this method, spatial patterns were defined to indicate ranges from high to low grout take within the foundation material. As can be observed in Figure 8, the highest grout take (shown in red) is located within the historic river channel. Other areas of high grout take were within the highly permeable F-bed Limestone.

Red zones on the kriging model shown in Figure 6 correspond to high grout take and therefore to pre-existing dissolution features and high permeability at the time of construction. That is, red zones indicate dissolution of gypsum that had already occurred prior to filling the reservoir. The discussion of recent grouting, later in this chapter, will show evidence that the dissolution front has moved in the past 20 years.

### Sinkholes

Four sinkholes (SD2, SD2S, SD3, and SD4) formed between 1992 and 1998 approximately 800 m downstream in the maintenance area of the dam (west abutment; LOD Final Report). The development of the sinkholes began with the appearance of concentric tension cracks followed

by settlement. The sinkholes appeared in a linear arrangement, approximately parallel to the dam axis. Sinkhole SD4 was excavated and observed for a year. The water level in this sinkhole did not fluctuate with changes in the reservoir level, but was sensitive to changes in the tailwater level. Fluctuating groundwater levels can lead to sinkhole development. Where an existing void or cavern has formed, the soil above has been alternately saturated and drained, resulting in reduction in pore pressure and eventual collapse.

The dissolution that produced the sinkholes in the downstream maintenance area most likely developed before dam construction. The surface of expression of these sinkholes since 1992 results from additional dissolution and collapse. All of the downstream sinkholes lie within the permeable F-bed Limestone, where solution features are common. The sinkholes are not connected hydraulically nor are they in stratigraphic continuity with the main reservoir. The drainage net for the west (right) abutment and downstream areas provided by Mosul Dam staff shows that the upland area drains toward these sinkholes (Figure 9).

The Butmah Anticline is double plunging, dipping more steeply to the south than to the east and north. Beds of the Jeribe Limestone Formation are exposed on the top of the anticline. The Chalky Series is exposed along the sides and overlies the GB0 layer. The Chalky Series is eroding from the sides of the anticline, especially where drainages have developed, resulting in the exposure of the GB0 layer. Along the southern side of the anticline, beds of the Chalky Series remain and dip steeply to the south. The line of sinkholes south of the regulating pool (SD2–SD4 in Figure 4) has formed by dissolution of steeply dipping gypsum beds by surface water and groundwater. They do not represent a threat to the integrity of the main dam.

A large sinkhole developed in February 2003, east of the emergency spillway when the pool elevation was at 325 m. The Mosul Dam staff filled the sinkhole the next day, with 1200 cu m of soil (LOD Final Report). The pool was dropped and then raised again, and the sinkhole reopened, meaning the fill from February sank into deeper parts of the dissolution feature. In June, it was refilled with another 2000 cu m of material, with the pool at 315 m. The pool was raised to 320 m and the sinkhole reopened, requiring another 1000 cu m of fill. Although there are insufficient data

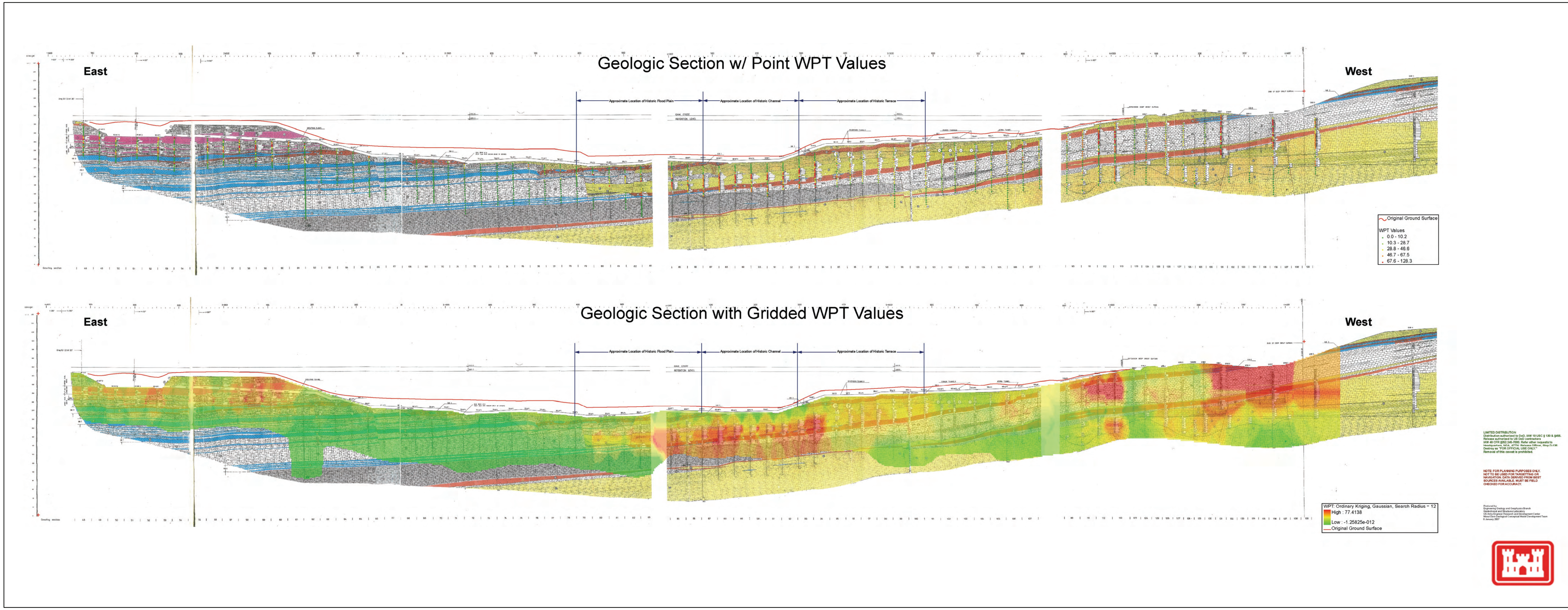


Figure 8. Geologic sections with water-pressure test values (upper figure) and kriging statistical analysis (lower figure) indicating areas of dissolution at the time of construction. The sections are from boreholes of the grout gallery under the dam. In the kriging (lower) section, red areas indicate zones of prehistoric and historic dissolution (M. L. Pearson, S. W. Broadfoot, J. R. Kelley, and T. E. McGill).

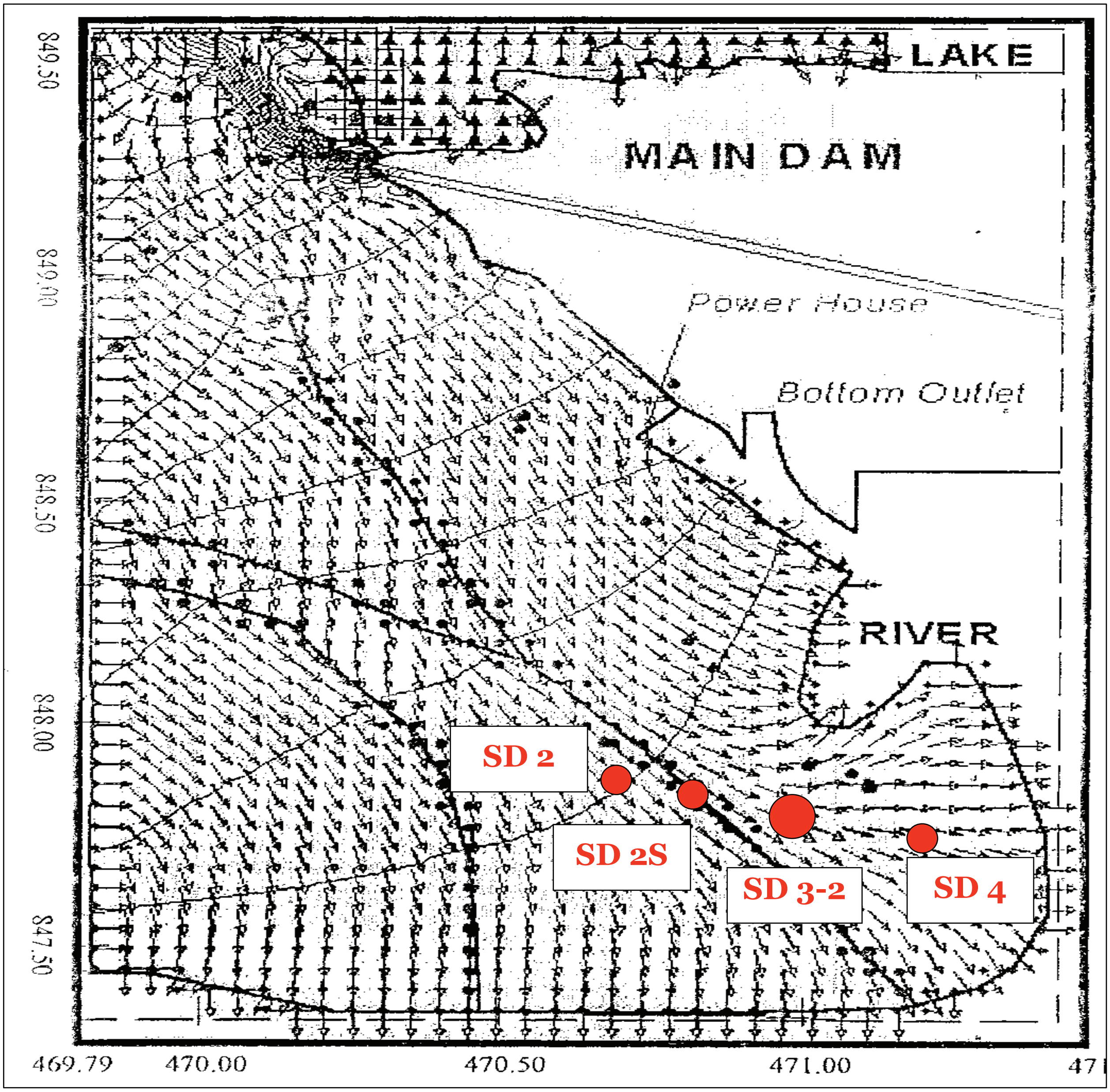


Figure 9. Drainage net provided by Mosul Dam staff indicates flow toward sinkholes in downstream maintenance area (sinkholes in red; modified by M. L. Pearson and J. R. Kelley).

to quantify the relationship between subsurface dissolution and pool level, it is clear that additional deep dissolution occurs or dissolution occurs at a faster rate in the same feature when the pool level is raised. This example illustrates that the visual portion of a sinkhole represents a very small percentage of the loss of material in the subsurface. Surface expression of a sinkhole may not occur until the visually obscured portion of the feature is well developed and very large.

More recently, a sinkhole (SD5) developed in July 2005 to the east of the saddle dam. Six borings were completed around the sinkhole and indicated that the sinkhole developed beneath overburden deposits and within layers of the Upper Marl Series. Data from the borings in the vicinity of SD5 show no offset in beds, so tectonic activity is not indicated. (See Figure 4 for locations of the sinkholes.)

Another cause for concern at Mosul Dam in recent years is a slide area reported upstream of the dam on the west bank. The slide is most likely related to the movement of beds of the Chalky Series over the underlying GB0 layer during erosion and not from tectonic forces. Although a fault has been mapped on the north side of the anticline north of the slide area, tectonic offset of beds is not indicated in the boring logs and presence of a near-surface fault is unlikely.

### Deterioration of rock quality

Rock cores were drilled during 1989 along a line roughly perpendicular to the saddle dam and parallel to the east side of the spillway, on the east (left) abutment. Descriptions of these cores show percentage of core recovery for stratigraphic intervals and rock quality designation (RQD). Quantitative RQD (Deere and Deere 1989) was originally introduced in 1964 to express the behavior of rock mass for tunneling purposes. RQD is defined as the sum of the length of core pieces greater than 4 in. (10 cm) divided by the total length of sampled core run, as a percentage. The values of RQD indicate proportionally the strength of a rock mass. Rock quality classification corresponding to RQD values is shown in Table 1. Low RQD values indicate poor engineering properties of the rock.

Most RQD values determined for rock on the east (left) abutment soon after construction of the dam ranged from the mid-40s to the mid-60s or higher. In 2006, cores were taken from the same area during assessment of sinkhole SD5 that daylighted in 2005 on the east (left) abutment near the crest of the spillway. For areas with RQD values as high as 65 in 1989, RQD had decreased to a range of 0 to 20 by 2006. Photographs of cores recovered in 2006 (Figure 10) clearly show low recovery rates and low RQD. This change indicates very active dissolution of rock in the east abutment between first filling of the reservoir and 2006. Some of the rock

Table 1. Values of rock quality designation, RQD, and corresponding rock-quality classification term (Deere and Deere 1989).

| Classification Based on RQD | |
|---|---|
| RQD | Rock Quality Classification |
| <25% | Very Poor |
| 25-50% | Poor |
| 50-75% | Fair |
| 75-90% | Good |
| 90-100% | Excellent |

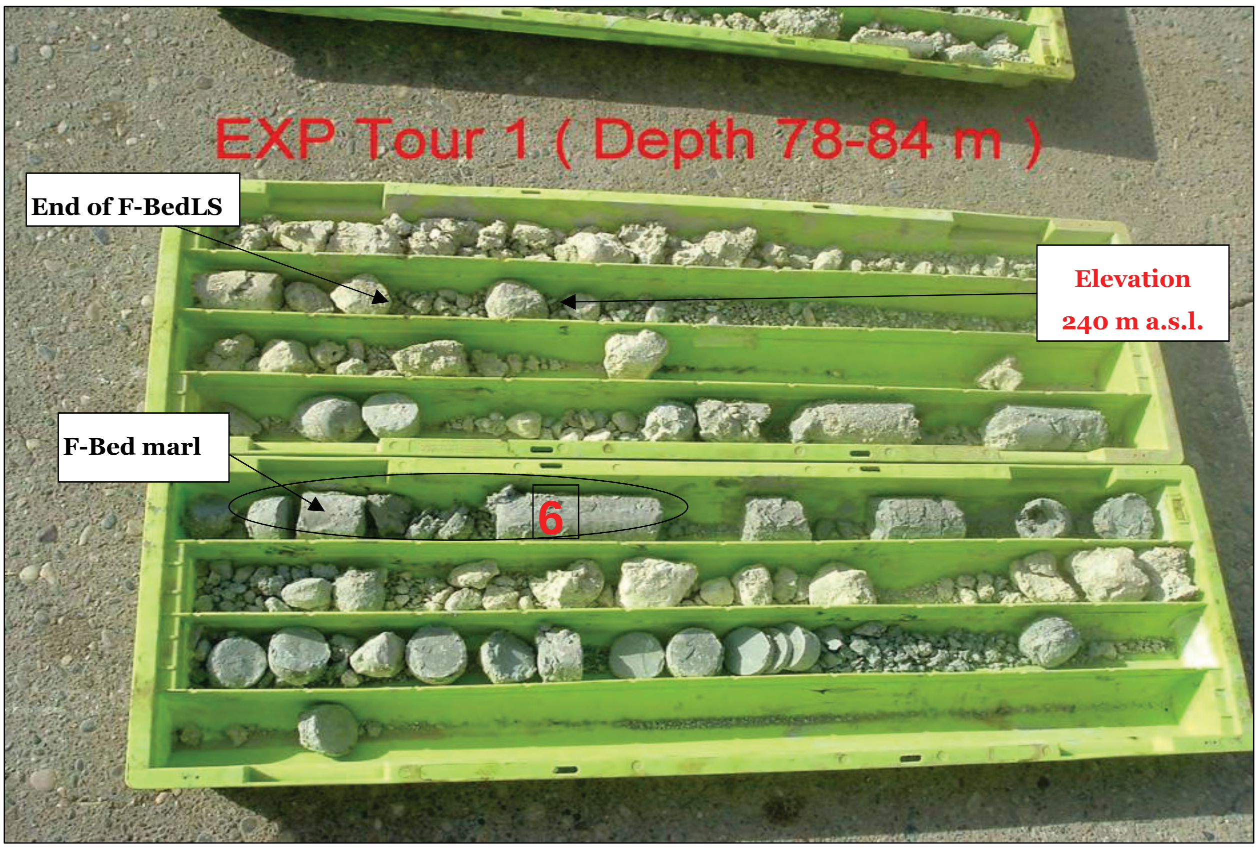


Figure 10. Core recovered from near sinkhole in residential area in 2006. Very small pieces of core and missing segments indicate RQD at or near zero, very poor rock quality.

that was considered competent to support the spillway and saddle dam during construction has deteriorated and may no longer be competent.

The appearance of a previously unknown sinkhole near the spillway crest in 2005 also shows this very active dissolution and degradation of rock quality in the east abutment. The potential for failure of the east (left) abutment has increased since construction.

The geologic units in the east abutment dip to the southeast, downstream and in the direction that allows gravity to feed impounded water from the reservoir into the subsurface. Raising the pool level increases the head on available water, increasing seepage or flow and thereby increasing the rate of subsurface dissolution and decreasing the rock quality.

### Grouting

The Mosul Dam site was grouted extensively during construction. Blanket grouting extended to a depth of 25 m (LOD, Vol 1). A central deep grout curtain also was completed beneath the main dam and spillway to a depth of 150 m (LOD, Vol 1). The grout curtain extends as a single-row curtain into the east (left) abutment.

A program of maintenance grouting was initiated immediately after the main grout curtain was emplaced, to address concern that arose during construction about continuing dissolution. A grouting gallery and two grouting plants support continuous grouting across the foundation. The gallery extends from the spillway on the east (left) abutment across to the west (right) abutment. Decisions on where and when to grout are based on changes in piezometer readings that show a decrease in the difference between upstream and downstream piezometer values and thus indicate loss of effectiveness of the grout curtain at the location of the piezometer pair. Grouting of the east abutment is accomplished outside the grouting gallery, from the surface in what is called the “open-air gallery.”

Water testing was done initially to determine the placement of grout within the foundation of the dam. Exploratory testing can be done to determine if cracks are dilating, if voids are filled with water, whether the flow is laminar or turbulent, and whether the cracks are being washed out. Grout hole testing is done by completing a simple water test and determining the Lugeon value of the hole before the application of grout.

The Lugeon unit is the most common and relevant permeability unit for grouting operations. It was developed in 1933 by Swiss geologist Maurice Lugeon and measures the quantity of water that can be forced out of a drill hole of a given length in 1 min under a set pressure (Warner 2004). One Lugeon is equivalent to 1 ℓ (0.26 gal) of lost water, per meter (3 ft, 4 in.) length of hole, per minute at approximately 10 bars of pressure (145 psi) (Warner 2004). A Lugeon can also be translated into rough permeability values or $1.3 \times 10^{-5}$ cm/sec (Houlsby 1990).

Generally, areas of permeability of 1 Lugeon do not need grouting and in fact cannot be grouted. Areas of permeability of 10 Lugeons warrant grouting to control seepage, and areas with values of 100 Lugeons have numerous relatively open joints or a few wide joints (Houlsby 1990).

In several reports in the library of documents provided to the ERDC, Lugeon values are discussed for the various layers of rock in the foundation. Lugeon values were determined for the foundation material prior to and just after construction (1980s). Those values have been recorded on several cross sections in the LOD. No Lugeon testing has been conducted since 1991 because of the excess pressures at the base of the gallery (A. T. Ayoub, Sep 2006, personal communication).

While the maintenance grouting program initiated in the 1980s has been continued rigorously at Mosul Dam, grouting practices worldwide have advanced well beyond the procedures currently in place at the dam. Weaver and Bruce (2007) provide essential information about current practices that would benefit the maintenance grouting program.

### Pattern of movement of grouting operations

Table 2 summarizes sections of the dam that were grouted during normal grouting operations in 2002 through 2006. This time interval represents recent and current conditions of grouting operations. The spreadsheet shows repeated cases where the outer two of three adjacent sections were grouted in one year and the central of the three sections had to be grouted in the following year. There are many examples where two or more adjacent sections were grouted one year and additional contiguous sections then required grouting the following year. Some sections are regrouted during three or more of the 5 years represented.

The most seriously challenged region shown on the spreadsheet is between sections 78 and 93, where the dam crosses the old stream channel. During the period 2002 through 2006, the only sections that required grout for filling large volumes in emergency mode were between sections 80 and 83, in the previous river channel under the main dam. Sections 94 through 115, toward the west (right) end of the dam and abutment, show a functioning grout curtain at least for the time interval included in the spreadsheet. That is, sections grouted one year do not require immediate regrouting. In dam records, the efficiency of the curtain in sections 100 to 111 is considered “very good” for this period, while the efficiency of the curtain

under sections 60 to 90 is described as “bimodal” or “variable, from good to poor.”

The current focus of grouting operations is in sections of the dam foundation and abutment that are east of areas of high Lugeon values in 1984. This shift in grouting activity indicates that the dissolution front under and downstream from the dam has moved to the east. Sections 82 and 83 were immediately east of the sections with highest Lugeon values in 1984, and at that time sections 78 and 79 showed low Lugeon values (green areas in Figure 8). A report on “exceptional grout takes” dated March 1987 (LOD, Vol 8) indicates that sections 80 and 81 were the center of concern at that time. Then, in 1989, section 79 required repeated grouting (data from boring logs in the LOD) and was grouted during 4 of the 5 years between 2002 and 2006. For this recent period, repeated grouting activity extends as far east as section 69. The pattern of recent grouting activity indicates that section 79 is in an advanced state of dissolution, and the front extends possibly as far as to the east as section 69. Thus, the dissolution front has advanced possibly as much as 10 sections of the dam or approximately 350 m in 20 years, averaging >17 m per year.

These trends in grouting operations show that the grout curtain is ephemeral in some parts of the dam foundation. Grouting the curtain at one location causes the water to move to an adjacent area and find a new path for dissolution and rock degradation, removing more of the already degraded remnants of rock mixed with grout. Several logs from boreholes drilled in the gallery in 1989 encountered grout material from previous grouting operations, in incompetent rock with very low RQD and low core recovery. Drilling logs show that remnants of grout were present throughout most of the length of the hole, with RQD values of zero in many intervals.

The patterns shown here indicate that dissolution occurs quickly (weeks or months rather than millennia of natural geologic processes) and can occur in sections of the dam that were recently grouted, at least in the area of the old river channel and eastward. Further, grouting operations are moving to the east with time, as the active dissolution front moves down-dip in southeasterly dipping rocks of the east (left) abutment. These patterns illustrate the increased risk of any time breaks in grouting, and the increased risk that would be associated with unavailability of grout materials or grouting equipment. Also, grouting from the “open-air” gallery on the east abutment is not shown in the summary or the annual report, so a

Table 2. Locations by dam section number of grouting operations since 2002 (summarized from annual reports by the Mosul Dam staff). Section 115 adjoins the west (right) abutment; section 65 is west of the upstream end of the main spillway, near where the dam adjoins the east abutment. The table does not include information about open-air grouting on the east abutment (Section numbers lower than 65).

Grout Takes - 2002 – 2006
Compiled by Dr. Monte Pearson and Julie R. Kelley

| | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 | 114 | 115 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2002 | | X | | X | | X | | X | | X | X | X | | X | X | X | | X | | | | | | X | | X | | | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | |
| 2003 | | | | X | | | | | | | | | | | | | X | | X | X | | | X | | | | | | X | | | | | | | | X | X | X | X | X | X | X | X | X | X | X | | | | |
| 2004 | | | | | X | | | | X | | | | X | | X | X | | X | | | X | X | X | | X | | X | X | | | | | | | | | | | | | | | | | X | X | X | | | | |
| 2005/2006 | | | | | X | | X | X | | | X | X | | | X | X | X | X | X | X | X | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| | Terrace and Channel Area | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| | Grouting in GB-0 @ elevation of + 160 m.a.s.l. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Dam crest 340 m.a.s.l. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Pool max 330 m.a.s.l. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

major part of the eastward movement of grouting operations is not captured in records from the grouting gallery.

### Historical seepage flows

Seepage flows have appeared as springs in the downstream riverbank and in the riverbed and have been present since reservoir impoundment in 1985. Currently, seepage flow values are measured at several locations at the dam. One is located in the access gallery, the second from the right side of the spillway and the third from the left side of the spillway. The largest flow, 170 ℓ/sec, is from the left side of the spillway and from limestone rocks of the abutment. These three seepages have different water chemistries because they are most likely flowing through different rock units (Wheeler 2004). Guzina et al. (1991) studied the seepage patterns through the dam and noted that intensive mineral dissolution began on impoundment when fresh water was introduced from the reservoir. The mineral content was greatest in the seepage water derived from the central part of the dam and corresponded to increases in permeability (due to washout of minerals from joint fractures and dissolution) of the gypsum layers there. Guzina et al. (1991) reported that a total of 13,000 tons of minerals was dissolved during the period February–August 1986 during the first partial impounding of the reservoir. The total mineral content of the water gradually dropped to a constant level (close to reservoir level). The average depth of the groundwater flow through the dam from the reservoir was 60 to 70 m below the ground surface as indicated by water temperature.

In several reports in the LOD, engineering observations stress that the outflow water from seeps is “clean and clear.” It is common in engineering practice for the greatest concern to arise where seep water or outflow water from piping through an embankment has visible suspended sediment, presumed to be washing out of the embankment. In the case of gypsum dissolution, large quantities of rock material can be removed by seep water with no visible evidence, that is, no suspended sediment. Most of the removal of rock material is by dissolution, leaving the water clear, rather than by visible, physical removal of suspended particles.

Additional information about seepage and water quality is presented in Chapter 7 of this report.

# 7 Geochemical Processes

## Groundwater and seep water

Dissolution of gypsum and anhydrite dominates the groundwater chemistry at the dam. The solutes associated with dissolution, especially calcium and sulfate, have been the primary focus of the ongoing water quality monitoring program. The major seep flows and a large array of piezometer wells within the gallery and free-field are shown in Figure 11. Within this monitoring network, a continuum in water composition between two end members is evident for the period January 2005 through September 2006. At one end of the continuum, reservoir water is relatively low in total dissolved solids (TDS) and near equilibrium with respect to calcite. At the other end, groundwater or seepage water is high in sulfate, indicating contact with the gypsum/anhydrite either in the relatively massive gypsum beds (GB0 through GB4) or dispersed within other strata (e.g., limestones, marls).

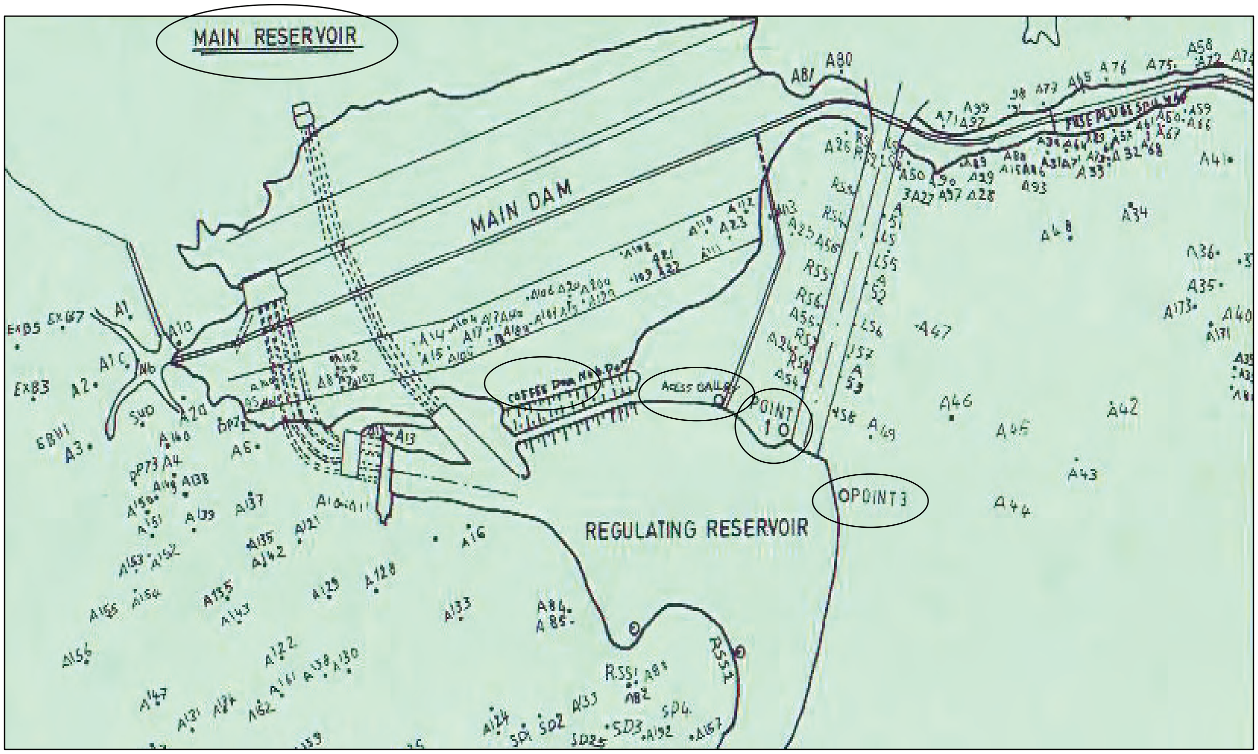


Figure 11. Locations of seepage monitoring and piezometers at Mosul Dam. Note especially Point 1 and Point 3, circled in red to the right-center of the map, corresponding to SP1 and SP3 in the text.

## Chemical composition of groundwater

Most of the available data for groundwater compositions, including data for chemical composition of reservoir water, show that all water in the region is slightly oversaturated with respect to calcite. Table 3 shows positive numbers in the column for saturation index of calcite (second column from the right), where positive numbers indicate that the water is unlikely to dissolve more calcite (a value of 0.0 would indicate that the water was in equilibrium with a given chemical). The condition of oversaturation for calcite is not surprising, given the prevalence of limestone in this arid terrain upstream from the reservoir. This observation is very important in that it suggests that further calcite dissolution from strata proximal to the dam is unlikely and attention can be focused on the dissolution and potential collapse of gypsum beds or rock units that include some gypsum.

Table 3. Analysis of representative geochemical data from Mosul Dam seeps, monitor wells, and reservoir.

| Site | Date | Cations | | | Carb. Hardn. | Total Hardn | Anions | | TDS | Saturation Index (SI) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pH (-) | Ca (ppm) | Mg (ppm) | (ppm) | (ppm) | $SO_4$ (ppm) | Cl (ppm) | TDS (ppm) | Calcite | Gypsum |
| Reservoir | Avg. (n=3) 4/06-7/06 | 8.4 | 32 | 18 | 160 | 150 | 94 | 45 | 160 | 0.69 | -1.94 |
| SP1 | 7/22/06 | 8 | 95 | 30 | 140 | 364 | 209 | 50 | 458 | 0.65 | -1.26 |
| SP1 ('05 peak) | 6/14/05 | (8) | 119 | -- | (150) | -- | 191 | -- | 670 | *(0.79)* | -1.15 |
| SP1 ('06 base) | 3/13/06 | (8) | 73 | -- | (150) | -- | 90 | -- | 332 | *(0.64)* | -1.59 |
| SP3 | 7/22/06 | 7.8 | 168 | 56 | 180 | 605 | 756 | 43 | 836 | 0.65 | -0.66 |
| SP3 ('05 peak) | 6/26/05 | (7.8) | 226 | -- | (180) | -- | 1536 | -- | 1945 | *(0.68)* | -0.36 |
| SP3 ('06 base) | 2/1/06 | (7.8) | 91 | -- | (180) | -- | 130 | -- | 650 | *(0.59)* | -1.38 |
| Access Gallery | 7/22/06 | 8.1 | 55 | 27 | 200 | 248 | 140 | 71 | 268 | 0.69 | -1.61 |
| Coffer Dam 6 | 7/22/06 | 7.9 | 149 | 29 | 100 | 494 | 183 | 82 | 730 | 0.59 | -1.15 |
| A6 Piezometer (W-bank, close) | Avg. (n=5) 6/04 – 9/06 | 8.7 | 74 | -- | (140) | -- | 144 | -- | 420 | *(1.23)* | -1.42 |
| A47 Piezometer (E-bank) | Avg. (n=4) 6/04-9/06 | 8 | 279 | -- | (180) | -- | 742 | -- | 1620 | *(1.06)* | -0.45 |
| SI's calculated with PHREEQC-2. Parentheses indicate estimated values of pH and alkalinity (carbonate hardness) needed to calculate the calcite SI. | | | | | | | | | | | |

Data for groundwater chemistry available for the ERDC study show that the water is undersaturated with respect to gypsum, although some interesting trends are evident (Table 3 and Figure 12). The analyses that most closely approach equilibrium are in samples associated with the east abutment. That is, less-negative values for saturation of SP3 water with gypsum (red oval in Figure 12) correspond to the removal of gypsum from the abutment and the increase in dissolved gypsum in seep water relative to reservoir water.

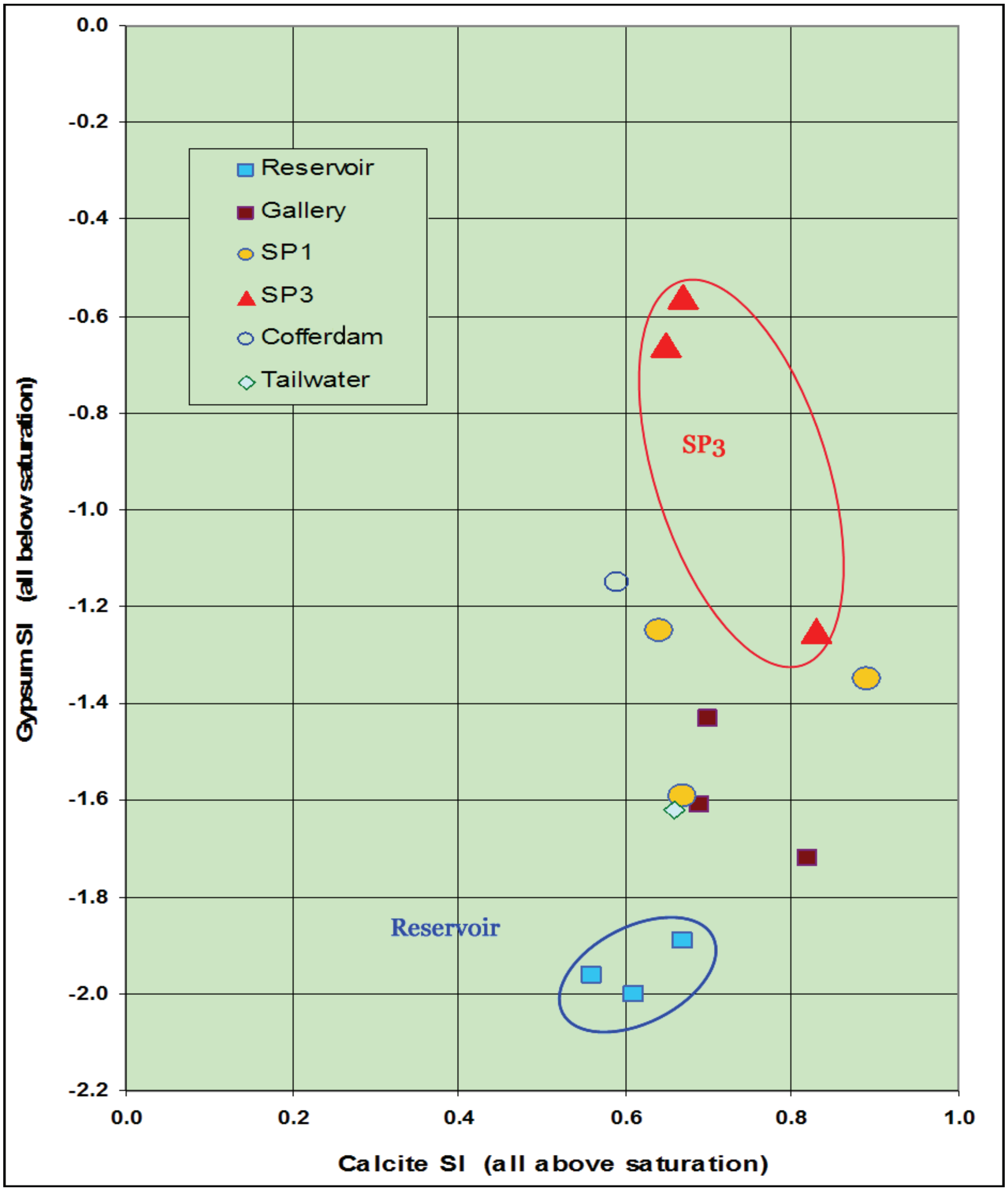


Figure 12. Chemical compositions of reservoir water and seep waters as represented by their saturation indexes for calcite (abscissa) versus gypsum (ordinate). Less-negative values for saturation of SP3 water (red oval) with gypsum correspond to the removal of gypsum from the abutment and increase in dissolved gypsum in seep water relative to reservoir water.

Water samples A47 and SP3 2005 peak (Table 3) were collected when the reservoir level was at its highest. These samples come closer to equilibrium (the two lowest negative numbers in the right-hand columns, Saturation Index) than any of the other samples. Virtually all of the other examples in the table are below -1.1, showing that the groundwater emerging from shallow layers of the east abutment is always undersaturated with respect

to gypsum, regardless of the TDS level. These trends are consistent with the conceptual hydrogeologic model in which the gypsum is still abundant in the east abutment, but there may be less gypsum available to the west where dissolution has been occurring for a longer time. That is, the dissolution front has advanced to the east into areas where gypsum is both abundant and readily soluble.

Movement of water through the east abutment is not controlled by large conduits; that is, it is not in simple open-channel flow. Flow through open channels would result in lower TDS whereas, at Mosul Dam, increased seepage flow is accompanied by increased TDS. The combination of rapid flow rate and high TDS indicates seepage through many small conduits and a large area of interface surface between rock and water relative to the volume of water moving through the rock.

Data from monitoring seepage at multiple locations (Figure 12) show strong, direct correlations between reservoir elevations and seepage flow rates (e.g., upper plots in Figures 13 and 14) and solute concentrations in the seepage (lower plots in Figures 13 and 14). The increased seepage-flow rate is readily attributable to the increased hydraulic gradient across the dam and east abutment. The very sharp rise in the SP3 flow when the reservoir elevation exceeds 318 m suggests that seepage has encountered a zone of higher permeability, or that increased hydraulic head increases the rates of dissolution and flow. The ERDC team did not have enough data to determine the specific cause of the obvious increased dissolution when the pool is above 318 m. The higher flow rates at SP3 (Figure 13) relative to SP1 (Figure 14) may result from a larger drainage domain to the east, or from a higher seepage rate through the east abutment than under or through the embankment, or may have multiple causes including these and others.

The increase in dissolved solids concentrations in both SP3 and SP1 may be attributed to the inundation of stratigraphically higher, gypsiferous strata. The higher concentrations of sulfate and TDS in the SP3 effluent reflect the greater continued presence of gypsum in the east abutment. The lower solute concentrations in the SP1 effluent may reflect the reduced presence of gypsum in the drained media, as well as a shorter residence time in the subsurface. A more detailed spatial analysis of the dissolution rates as a function of flow and other variables is necessary to distinguish among several possible causes for the observed trends in dissolution.

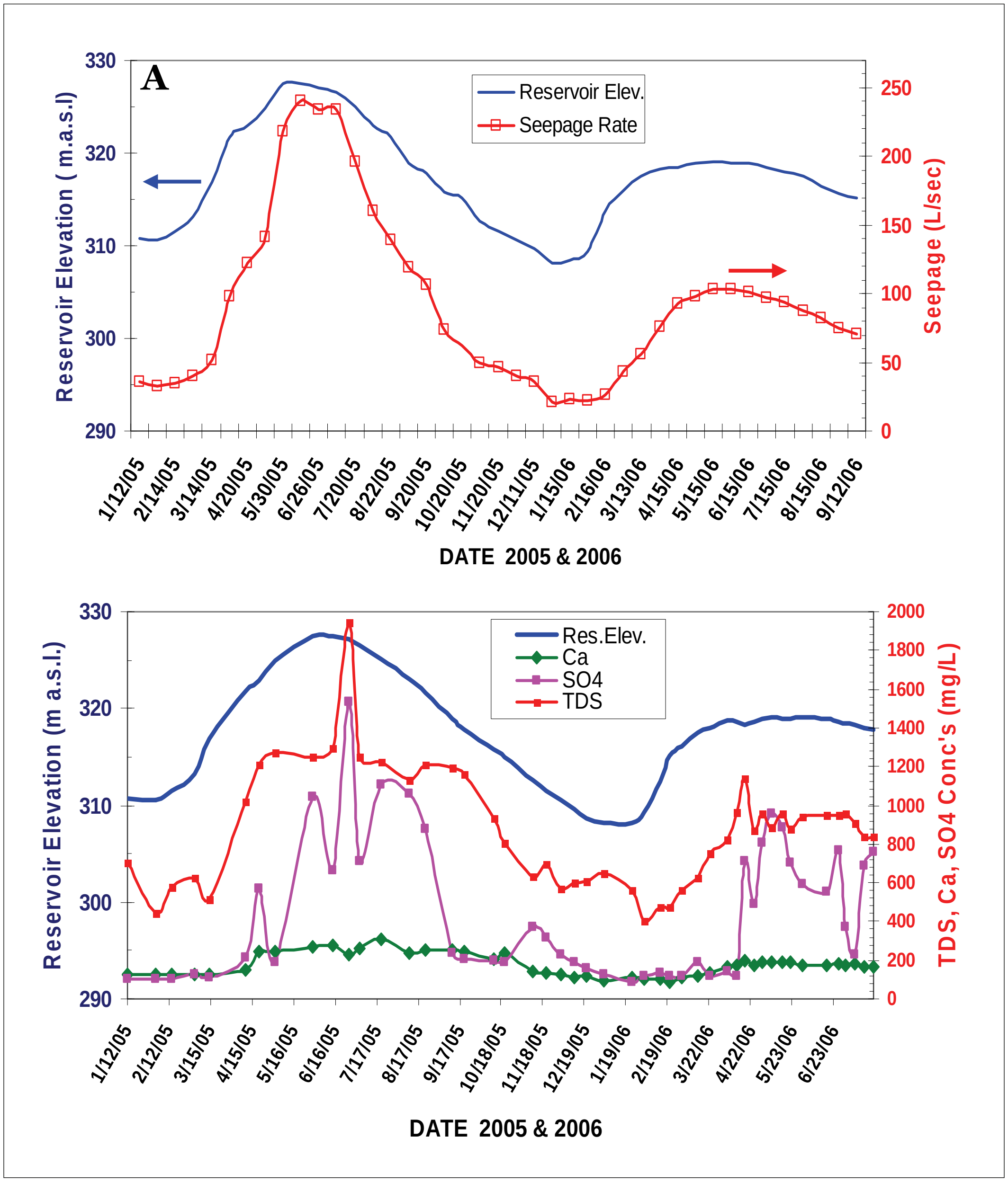


Figure 13. For Seepage Point Number 3 (SP3, east of spillway), trends in seepage rates (upper plot, red line, right scale) and solute concentrations (lower plot, right scale) are strongly correlated to very similar trends in reservoir elevation (blue lines, left scales). Data are for an 18-month period in 2005-2006.

Based on data for SP3 in 2005, the average bulk dissolution of gypsum is 5.8 $m^3 \cdot day^{-1}$. Dissolution associated with SP1 for the same period is only 0.17 $m^3 \cdot day^{-1}$. These rates are much lower in the first half of 2006 (limit of available data), presumably in response to holding the pool elevation at or below 318 m. The amounts indicated for recent dissolution are far smaller than estimates of the initial dissolution rates of a total of 13,000 tons of minerals dissolved during the period from February to August 1986

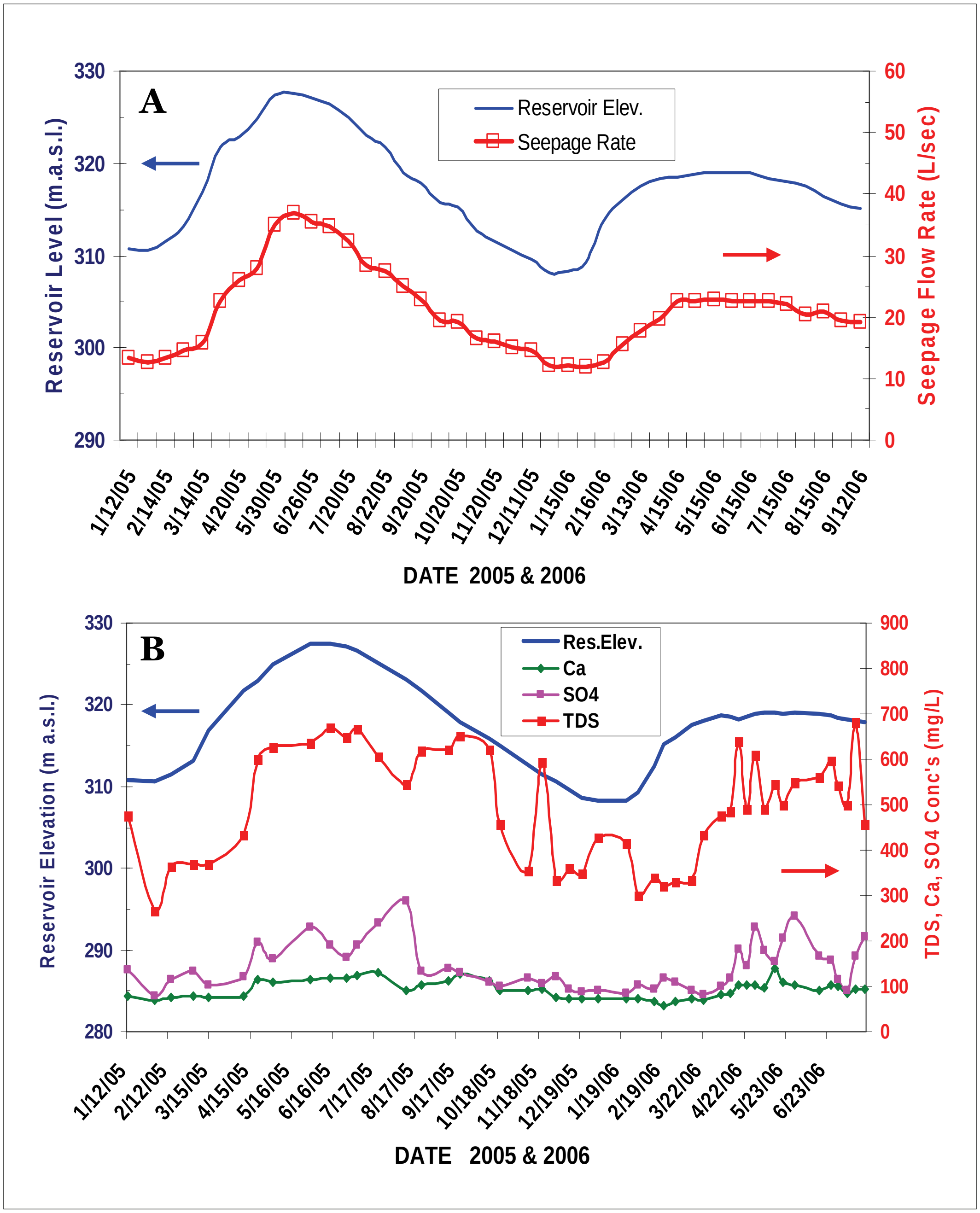


Figure 14. Data from Seepage Point Number 1 (SP1, west of spillway) showing trends in both seepage rates (upper plot, red line, right scale) and solute concentrations (lower plot, right scale) during an 18-month period in 2005-2006. Trends correlate strongly with trends in reservoir elevation (blue lines, left scales).

(~24 $m^3 \bullet day^{-1}$) as reported by Guzina et al. (1991). The 1986 estimates indicated that dissolution was greatest at the central part of the dam, and that the average depth of the groundwater flow through the dam from the reservoir was 60 to 70 m below the ground surface, as indicated by water temperature.

With only limited data from discontinuous and widely spaced time intervals (1986, 2005–06), it is not possible to distinguish which variables control the rate of dissolution. Lower TDS in 2006 relative to 1986 could be attributable to movement of the dissolution front, to the depth of flow represented by seepage collection, to grouting having moved the focus of dissolution, to grouting having decreased the rate of dissolution, or to combinations of these and other factors. Seepage monitoring in 2005–06 probably captures only the shallowest flow, and may not be comparable to the data reported in 1986. However, even the reduced dissolution rates are substantial and capable of generating structural instabilities in the geologic media of the foundation and east abutment.

# 8 Summary of Engineering Implications

Sinkholes that have reached the surface recently on the east abutment indicate large-scale dissolution in the subsurface. Sinkholes downstream from the dam on the west bank are not hydraulically connected to rock units in the reservoir floor, and do not represent a threat to dam integrity. Rock quality, grout-curtain efficiency as related to piezometer data, sinkhole development, sinkhole retreatment, dissolution rates of rock material, and water chemistry (TDS) collectively indicate that the dissolution front is moving to the east and downstream. The geologic conceptual model supports these lines of evidence for movement of the dissolution front, and indicates the increasing importance of piezometers on the east abutment. The same evidence also reveals the critical need to include open-air grouting east of the grouting gallery as a component of the enhanced grouting program. The pattern of regrouting in and between recently grouted sections of the dam shows that grouting at one location causes the flow path (seepage) of subsurface water to move to another location, but does not stop the seepage.

Following are lists of geologic and geochemical factors that are important to engineering decisions about Mosul Dam.

## Implications of the general geologic setting

- Subsurface dissolution at this site is a prehistoric process, now progressing at a faster rate than before human-caused processes were introduced.
- Mineralogic variability within rock units resulted from original depositional processes that created interfaces and zones of weakness within individual beds. These natural zones of weakness now function as ingress points for seep water and allow dissolution zones to move vertically and horizontally.
- Dip of geologic units in the east (left) abutment and the regional slope to the southeast and downstream from the reservoir promote water movement in the subsurface to the southeast.
- Rock units on east (left) abutment dip 6 deg to south. Relatively flat-lying rocks to the east and steeply dipping rock units to the west of the dam help control the direction of water movement driven by the hydraulic head created by the reservoir pool.

- Sinkholes are visible evidence of extensive subsurface dissolution. The volume of a sinkhole visible from the surface is a small percentage of the total dissolved volume of rock. Sinkholes do not appear at the surface until a large volume of material has been dissolved and removed by seep water.
- The dissolution front is moving to the east and south from the pool.
- Rock quality is deteriorating near the spillway, east and south of the pool.
- Permeability increases as rock quality decreases.

## Implications of dissolution and groundwater movement

- Dissolution is occurring at a faster rate than it did before construction of the dam. The rate of subsurface erosion has been increased by the presence of the reservoir.
- Dissolution is currently active in the dam foundation and abutments, a process that is not visible until sinkholes reach the surface.
- The reservoir provides an infinite supply of fresh water, undersaturated relative to gypsum, so gypsum dissolves readily at ordinary temperature and pressure.
- The amount and rate of dissolution in the east abutment increases when pool is at or above 318 m.
- For seepage east of the spillway, the dissolution-rate curve is steeper than the pool-elevation curve. This means seepage east of the spillway increases at a greater rate than the increase in pool level, and seepage and dissolution are not in equilibrium with the pool level.
- The sudden increase in slope of the dissolution curve at a pool depth of 318 m above sea level shows the increased rate of dissolution when the pool is above this level, leading to the recommendation that the pool should not be raised above 318 m.
- Movement of water through the east abutment is not controlled by large conduits; that is, it is not in simple open-channel flow. Flow through open channels would result in lower total dissolved solids whereas, at Mosul Dam, increased seepage flow is accompanied by increased TDS. Instead, the combination of rapid flow rate and high TDS indicates seepage through many small conduits and a large area of interface surface between rock and water relative to the volume of water moving through the rock.

## Implications of grouting and performance of grout curtain

- The pattern of regrouting in and between recently grouted sections of the dam shows that grouting at one location causes the flow path (seepage) of subsurface water to move to another location, but does not stop the seepage.
- Seepage under and around the dam began as the reservoir was filling. The original grout curtain has never been effective as a flow barrier.
- Continuous maintenance grouting has not created an effective grout curtain.
- At least since 2002, there has been a general movement of grouting operations toward the east abutment. (The ERDC team had no data for previous years.)
- Deterioration of rock quality and the recent appearance of sinkholes in the east abutment, along with other evidence, indicate that the Enhanced Grouting Program for Mosul Dam must include grouting to the east, well beyond the grouting gallery.
- The frequency of regrouting within a single section of the dam indicates that dissolution of gypsum is occurring at an accelerated rate, relative to natural processes.
- High grout-curtain efficiency in western sections of the dam, as shown by less frequent regrouting, indicates less seepage through the west abutment, at least partly controlled by the geologic structure of the west (right) abutment (steeply dipping beds).

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**14. ABSTRACT**

The geologic setting of Mosul Dam is critically important for its engineering implications and its usefulness and contribution to engineering and operational decisions about the dam. The dam was constructed on alternating and highly variable units of gypsum, anhydrite, marl, and limestone, each of which is soluble in water under the environmental and hydrogeologic conditions of the dam. From a geologic standpoint, the foundation is very poor, and the site geology is the principal cause of continuing intense concern about the safety of the structure. Mineralogic variability within rock units resulted from original depositional processes that created interfaces and zones of weakness within individual beds. These natural zones of weakness now function as ingress points for seep water and allow dissolution zones to move vertically and horizontally. Dissolution is occurring at a faster rate than natural geologic processes. Sinkholes that have reached the surface recently on the east abutment indicate large-scale dissolution in the subsurface. Rock quality, grout-curtain

(Continued)

**15. SUBJECT TERMS**

| | | | |
|---|---|---|---|
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| Dam safety | Evaporite geochemistry | Groundwater chemistry | Sabkha |
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**14. ABSTRACT (Concluded)**

efficiency as related to piezometer data, sinkhole development, sinkhole retreatment, dissolution rates of rock material, and water chemistry (total dissolved solids) collectively indicate that the dissolution front is moving to the east and downstream. The rate of subsurface dissolution has been increased by the presence of the reservoir. The pattern of regrouting in and between recently grouted sections of the dam shows that grouting at one location causes the flow path (seepage) of subsurface water to move to another location, but does not stop the seepage. At or above a pool depth of 318 m above sea level, the rate of subsurface dissolution increases markedly, leading to the recommendation that the pool not be raised above 318 m.